WAVES OF THE SEA AND OTHER WATER-WAVES

VAUGHAN CORNISH

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AND OTHER WATER WAVES

BY

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WITH 50 PHOTOGRAPHS TAKEN BY THE AUTHOR

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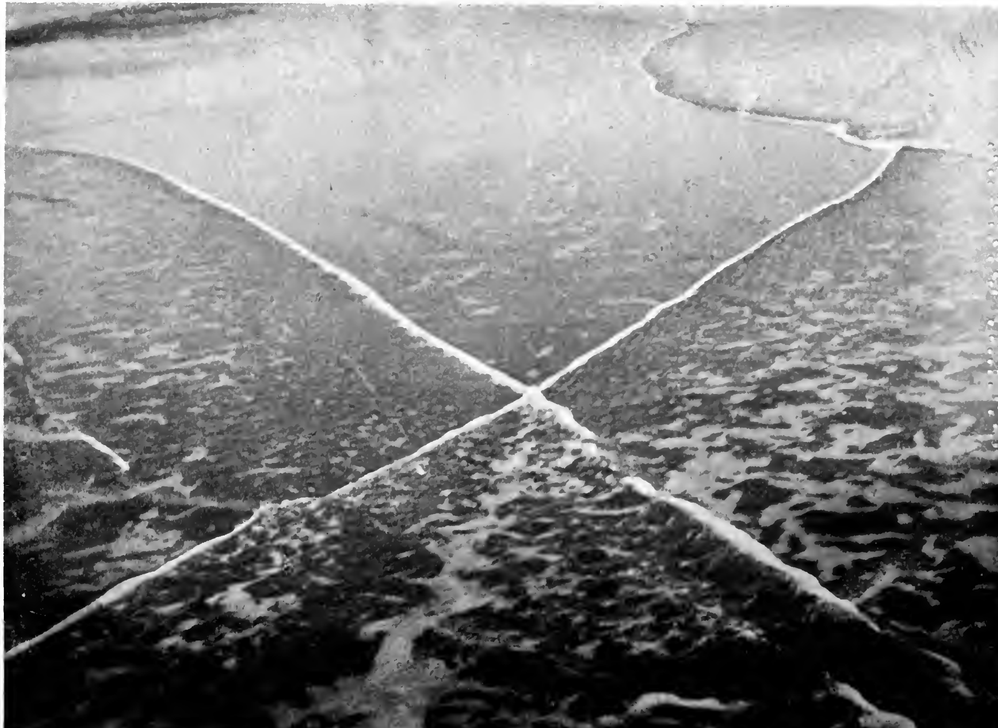

WAVES MEETING AND CROSSING IN VERY SHALLOW WATER.

Frontispiece

TO

SIR CLEMENTS R. MARKHAM, K.C.B., F.R.S.

VICE-PRESIDENT AND PAST PRESIDENT

OF THE

ROYAL GEOGRAPHICAL SOCIETY

IN TOKEN OF

SINCERE REGARD AND VENERATION

I DEDICATE THIS BOOK

V. C.

PREFACE

MOST of us have felt the fascination of a wave. The waves of the sea, which are the prototype of all the phenomena which we now call waves, are perhaps the most fascinating of all. Great as is the beauty of their form, the mystery of their motion is the greater charm. For while they move they live and have a being, which, like our own, is but momentarily associated with the matter of which they are formed. The wave preserves its individuality, its recognisable though not unchanging form, its energy, partly active, partly in reserve, whilst its material substance is constantly rejected and renewed. Of all manifestations of the inorganic world it is most like a living being. Yet when we watch it to its end we find none of the sad accompaniments of the exhaustion of life. It is most beautiful at the last, as it culminates to its fall and breaks in seething foam.

There are two aspects of sea waves which particularly attract our admiration. The first is that of a storm at sea, the second is the surf which comes in during calm weather upon a shore facing the open ocean, the breakers booming like minute guns. The first indicates the fury of the wind, but it is the second which we almost instinctively recognise as affording the best index of the greatness of the expanse of water.

These things, and others of a like nature, I have watched for many years, and I have set down in this book what I have been able to add to former knowledge.

I have written to inform the mind, not to stir the imagination. The appearances are familiar and recurrent, and I do not attempt to recall them by much word-painting, but the precise observation and measurement of waves, and the discovery of the mode of their production, are matters of difficulty, and to these I have given myself.

My investigations on water waves have been prosecuted during the last fifteen years. They have been made in many parts of the world, which I have visited principally for the study of surface waves of different kinds. The chief results as far as they relate to water waves are contained in this volume, which contains also a critical examination of observations made by a number of seamen and others upon the size and speed of ocean waves.

Most of Part III., relating to tidal bores and other waves in rivers, was published in the *Geographical Journal* and in *Engineering* in 1906, but Parts I. and II., which relate to waves of the sea, are new, and were written in 1909-10.

Side by side with the observations of water waves, I have during the same period (*i.e.*, since 1895) been investigating the progressive transverse ridges which are produced in sand and snow by the action of water or wind, and I have made observations upon earthquakes and other wave-phenomena which come within the province of physical geography. These I intend to publish later.

August, 1910. VAUGHAN CORNISH.

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PART I

ON THE SIZE AND SPEED OF DEEP-SEA WAVES

CHAPTER I

Introduction—Waves on ponds—Waves on lakes—Coniston Water—Lake of Geneva—Lake Superior—Waves in semi-enclosed seas—Western Mediterranean—China Sea.

Introduction

MEASUREMENTS of waves at sea by means of the eye are not susceptible of great accuracy; but the irregularity of the waves themselves is so considerable, especially in their most important condition, which is during storms, that it is more useful to measure many waves somewhat roughly than to obtain (even if it be possible) the precise measurement of a few. The advantage of the mere number of observations does not, however, apply when we pass from rough measurements by careful observers to mere guessing at the dimensions of waves as seen from on board ship. Measurements of the height of waves, for instance, taken in the usual way by finding the height above the ship's water-line from which a neighbouring wave-crest just intercepts the horizon, are believed to be accurate to within 1 foot in 10 when made by a practised observer. This was the estimate of the late Lieutenant Paris, of the French Navy, for his observations, and the late Lord Kelvin informed me that he relied upon his own measurements to the same extent. When, however, an unpractised observer, judging merely by the look of things from the deck of a ship, guesses the height and length of waves, it is possible for him to err much more widely than he would on the land, where he stands on a firm platform, with objects of known size in the neighbourhood to afford a scale. The rolling of the ship, in particular, alters the apparent direction of the vertical so as to mislead the judgment as to height. It is difficult to say how widely these guesses may depart from fact, but I do not think it unlikely that waves 20 feet high may, according to the circumstances, be guessed by unpractised or careless observers at anything from 10 to 30 feet. This is a range of error of 100 per cent. as against the 10 per cent. of the practised observer.

While, therefore, in dealing with the data before me, I have been anxious to obtain numerous records, I have been still more anxious not to include any which might belong to the category of misleading guesses. As far as possible, I have relied upon figures in which the observer has explained his method of measurement, and detailed the attendant circumstances of wind, weather, and environment. This may have led to the rejection for the purpose of this book of good measurements, but the importance of all measurements or estimates of the size of sea waves being accompanied by a statement of the method of observation and the attendant circumstances cannot be too strongly emphasised.

The relation between the wave-length in deep water and the period (or time which elapses between the passage of a fixed point by two succeeding wave-crests) has been calculated mathematically, and verified by observation. I have, therefore, in what follows applied the formula thus obtained, viz.:

$$\text{Wave length} = 5\tfrac{1}{8} \times \text{square of period},$$

to obtain the wave-length when only the period has been measured. In all cases, however, the reader is informed which observation was made, that of length or period.

WAVES ON PONDS

As the sea is always heaving with the disturbance due to former winds, the commencement of the wave-making action of wind is best observed on smaller sheets of water. In a rock pool, 20 feet in diameter, under High Peak, Sidmouth, Devon, I have measured waves of 1 inch wave-length at the windward end, and $4\frac{1}{8}$ inches at the leeward end, the wind having the force of a gale. Thus if we take the average length of the waves to be $2\frac{1}{2}$ inches, there was in this small pool a series of ninety consecutive waves, the longest of which was 1-60th of the length of the series.

On the Round Pond in Kensington Gardens, London, 670 feet in diameter, the water on an absolutely still day has a glassy surface, but any breath of air sufficient to be felt upon the cheek is enough to ruffle its surface and to do away with the mirror-like reflection. It will then be seen that the area of ruffled water has been instantaneously covered with an almost uniform pattern of little waves about an inch in length from crest to crest. As the minutes pass during which the breeze continues, the height and length of the waves to leeward increases, but those on the windward edge of the ruffled water remain of the original size. Soon the whole pond, except a few feet at the windward end, is covered with waves travelling before the wind whose size increases regularly from the windward to the leeward shore. The maximum size attained at the latter place depends to some extent upon the strength of the wind, but even in a whole gale (October 6, 1901) the little breakers on the shelving lee shore followed one another at intervals of only 1 second.[1] The wave-length was not measured, but appeared to be about 3 feet. The whole of this effect was soon produced, being a matter of minutes; the height of the waves quickly diminished when the wind lulled, and could be seen to increase instantaneously when squalls occurred, the height increasing by a considerable fraction during a squall lasting four minutes.

If we take the greatest length of waves observed in the Round Pond on the day referred to as 3 feet, and adopt the simple mean of the shortest (1 inch) and the longest (36 inch) wave as the average wave-length for the pond during a gale, we find that there is then a series of 436 consecutive waves, of which the longest is 1-223rd of the length of the series, or of the length of fetch of the wind, or of the length of run of the waves.

On the Serpentine Water in Hyde Park, a much larger pond, the shape of which, however, is not favourable to the development of waves, I measured those produced in a strong SW. breeze, going out

[1] The calculated length of a 1-second wave in deep water is 5 feet. The velocity of the wind in London was 50 statute miles per hour.

in a boat not very far from the lee end, where I was sure of a sufficient depth of water for the purpose. Measurements with a wooden rule repeated during the course of half an hour gave 3 feet wave-length and a height from trough to crest of about 2 inches.

In ponds, therefore, we see that when the wind raises waves at all they must be numerous, and that even the longest must be a small fraction of length of the series, and that the fraction decreases as the length of the pond increases. The steepness of the waves formed by wind upon ponds is also found to be small as compared, for instance, with the waves which may sometimes be seen caused by obstructions in a river. Thus the height of the waves in the Serpentine was only 1-18th of their length.

WAVES ON LAKES

Coniston Water

We now proceed to observations on a larger sheet of water, the Lake of Coniston, or Coniston Water, in Lancashire. They were taken near the upper end of the lake, at a distance of 7 statute miles from the lower end. The sheet of water is narrow and nearly straight, the lower end about

S. by W. from the upper. When the wind blew up the lake with the force of half a gale I found that the waves near the upper end succeeded each other at intervals of 2 seconds, corresponding to a wave-length in deep water of 20 feet. At a later date Mr. Hamil, a seaman of experience, and captain of the steam gondola which plies on the lake, sent me the following observations which he made upon the larger waves produced in a whole gale of wind.

On September 3, 1902, at 8 a.m., there was a light wind blowing up the lake, *i.e.*, from the south. At 10 a.m. it rose to a gale, the wind shifting to a little W. of S. Mr. Hamil timed the waves at Yewdale Beck, near the upper end of the lake, with the following results :

	Waves passing point of observation.	Waves breaking on beach.
10.30 a.m.	... 27 per minute	...
10.32 a.m.	...	... 24 per minute
11.0 a.m.	... 23 ,, ,,	...
11.2 a.m.	...	... 22 ,, ,,
11.30 a.m.	... 21 ,, ,,	...
11.32 a.m.	...	... 20 ,, ,,
12.0 a.m.	... 21 ,, ,,	...
12.2 a.m.	...	... 20 ,, ,,

Thus the period appeared to be constant after 11.30 a.m.—*i.e.*, an hour and a half after the gale commenced. The length of wave in deep water corresponding to the observed period of 3 seconds is 46 feet. The distance from the lower end of the lake being 7 statute miles, or 36,960 feet, the length attained by the waves is 1-803rd of this distance. If we take the average length of the series of waves as 23 feet (since when they commence their length is very small), the number of waves in series from end to end of the lake was 1,608.

The wind conditions were similar to those described for the Round Pond at Kensington and for the Rock Pool at Sidmouth. Thus we see that the length of the storm-waves is increased when the length of the sheet of water is increased, but more slowly.

The above, however, are not the greatest waves which can be formed on Coniston Water, although they are probably about as large as are formed in ordinary gales. The following observations supplied to me by Mr. Hamil illustrate the way in which waves larger than ordinary are produced. They indicate a fact (which we shall find illustrated later when dealing with the great waves of high southern latitudes—*e.g.*, between the Cape of Good Hope and Australia) that the wave-raising power of wind is much greater when operating upon water already in waves than upon nearly smooth water.

Mr. Hamil finds that the largest waves on

Coniston Water are only formed when, after about three days of steady wind blowing along the length of the lake has produced a steady "run" of waves, it comes on to blow very hard in the same direction. Under such circumstances he recorded, near the upper end, a wave-length of 65 feet and a height of 5 feet. These measurements were made against the side of the steam gondola. He relies upon the length to less than 5 feet either way—*i.e.*, is sure that the waves were more than 60 and less than 70 feet long. The determination of height he found more difficult. The wave-length attained under these somewhat rare conditions was 1-569th of the length of the whole series. The length of wave was 13 times the height. Assuming the same steepness of water for ordinary gales as for the above unusual storms, the height of wave corresponding to the wave-length of 46 feet would be 3½ feet, and this, I suppose, is seldom much exceeded on Coniston Water.

The Lake of Geneva

On Lake Leman, or the Lake of Geneva, Dr. F. A. Forel records during storms wave-periods of 4.7 seconds at Morges and 5.0 at the town of Geneva. The longest run which a wave could have before reaching Morges is 27 statute miles, and the calculated wave-length in deep water for a period of 4.7 seconds is 113 feet. The length of run possible at the town of Geneva, which is situated at the lower extremity of the lake, is 43 statute miles, and the wave-length corresponding to a period of 5 seconds is 128 feet. At Morges, therefore, the length of the storm-waves was 1-1261 of the length of the series and at Geneva 1-1774. If we suppose the wind blowing down the lake, and at the Geneva end making waves 128 feet long, then if we take as before the average length of waves on the lake to be one-half as long, the number of the waves in the series, from end to end of the lake, is 3,548.

The following heights of waves on the lake are recorded by Thos. Stevenson[1] as having been observed by Buckie at the distances stated from windward shore, viz.:

Height of Wave in feet.	Length of Fetch in miles.
7.0	31
7.0	38
8.0	38
8.0	40

[1] *Vide* article, "Harbours," "Encyclopædia Britannica," 9th edition. Of all the bodies of water cited by Stevenson in his table of the increase of height with length of fetch, the Lake of Geneva is the only one which is wholly enclosed. Many of the others are, moreover, shallow or affected by strong currents.

The greatest length (calculated from the observed period) is 15.4 times the greatest height.

Lake Superior

On Lake Superior waves have been carefully measured from the shore by Colonel D. D. Gaillard, Corps of Engineers, U.S.A. For the size of the waves out in the deep water of the lake, he has, however, had to obtain evidence from the captains of vessels. He writes:[1]

"As the result of inquiries of vessel captains who have navigated Lake Superior for many years, and who have, in some cases, made a special note of the fact that in unusually severe storms the horizon could not be seen from the wheelhouse when the ship was in the trough of the sea, on account of adjacent wave-crests, it seems probable that during unusually severe storms upon Lake Superior, which occur only at intervals of several years, waves may be encountered in deep water of a height of from 20 to 25 feet and a length of 275 to 325 feet."

He adds that the waves on Lake Superior are larger than occur on any other of this chain of great lakes.

[1] "Wave Action in Relation to Engineering Structures" (Washington Government Printing Office, 1904), p. 82.

In the Duluth Canal at the western end of Lake Superior Colonel Gaillard during 1901 and 1902 frequently measured waves 200 feet in length, occasionally 250, and once 275 feet, in a depth of not more than 27 feet of water. The velocity of such waves is reduced in water of this depth and they close in upon one another, their wave-length diminishing. The measurements taken by Colonel Gaillard in somewhat shallow water therefore show that the estimates of wave-length made by the captains of vessels were not excessive, and that we may safely say that a length of 300 feet is attained during exceptionally severe storms by the waves of Lake Superior. The possible length of fetch of wind and length of run of the waves at Duluth is 298 statute miles or 259 nautical miles, so that the greatest wave-length is 1-5248th of the length of the lake, and if the average wave-length of the series be 150 feet, there would be 10,496 successive waves simultaneously between windward and leeward shore. Thus again we find the steady growth of wave-length with the length of the sheet of water, the increase of wave-length taking place, however, more slowly.

Taking the height of the waves during severe storms on this lake as 22½ feet and their length as 300, we find that the length is 13.3 times the height, which is nearly the same as that (13) found for an exceptional storm on Coniston Water.

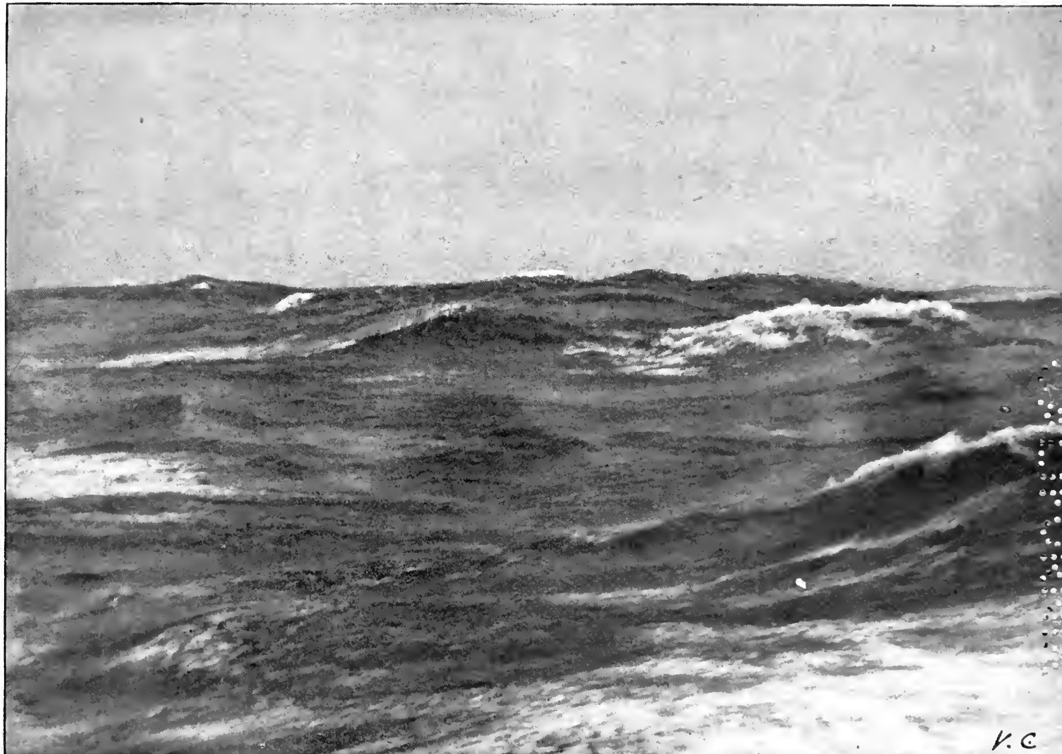
WAVES IN SEMI-ENCLOSED SEAS OF CONSIDERABLE DEPTH

Waves in the Western Mediterranean

The Western Mediterranean is about 1,000 statute miles from east to west, but its area is somewhat broken up by islands. The depths are great and the tidal currents small, so that observations of waves are useful for the determination of dimensions due to the mere action of wind on deep water.

On April 7, 1899, I sailed from Marseilles at 4 p.m. on the Orient liner *Orizaba*, bound for Naples, the weather being fair. Next morning, the 8th, when nearing the Straits of Bonifacio, there was a heavy sea directly following the ship, the wind having risen during the night and having now the force of a moderate gale. The waves were not running in a single series of parallel ridges, but with a good deal of crossing, and the characteristic feature of the scene was the number of bursting billows of more or less pyramidal form produced by the meeting at an acute angle of waves running not quite in the same direction, These waves, curling over in a cusp and breaking, flecked the surface of deep blue water with white foam which reflected the bright beams of the sun shining through the spray. I set myself to measure the height of these waves at the times of their greatest elevation. Standing on the bulwark rails of the spar deck, while holding to the steel uprights which supported the promenade deck, I found that my eye was on a level with the crests of the highest waves when 22 feet above the flotation line. The position of the latter I obtained from the commander, who informed me that its then position was 3 feet below the Plimsoll mark. The height of the deck above the Plimsoll mark was known from the scale plan of the ship. The ship did not pitch, and her rolling was so slow that it was fairly easy to make the observation when on an even keel. Thus the height from trough to crest of the pyramidal waves, which were the characteristic waves of the day, was ascertained with some approach to accuracy to be 22 feet.

I desired to ascertain the length of the waves, which were travelling in the same direction as the ship, but as usual was unable to watch a wave-crest running the whole length of the vessel. The length between two convexities near the ship's side, viewed simultaneously, I judged to be



A MODERATE GALE IN THE MEDITERRANEAN.

130 feet, using the length of the promenade deck as standard of measurement. This estimate is quite out of harmony with the successive observation of following waves. The speed of the vessel was 14 knots and the waves travelled past the ship at a very considerable speed. They succeeded one another at an average interval of 17 seconds. This determination by itself does not permit the wave-length to be calculated from a simple formula,[1] but it is satisfied by a true period of 8 to 9 seconds with length of 328 to 415 feet. Seven seconds (with a wave-length 250 feet) is definitely too small, and 10 seconds (with wave length 512 feet) is definitely too much. It is quite inconsistent with a length of 130 feet, which corresponds to a speed of only 15 knots, which is scarcely greater than that of the ship, and it seems likely that this estimate of the wave-length was in fact due to the transverse waves caused by the ship's own motion, which for her then speed of 14 knots have a length of 110 feet.

It appears, therefore, that the average wave-length was not less than 328 feet (an 8-seconds wave).

The wind was westerly, and the sea-room about

[1] It can be calculated, however; see Monthly Chart, North Atlantic, September, 1909, published by the Meteorological Committee.

300 statute or 260 geographical miles. This distance from the windward shores is the same as the maximum possible on Lake Superior, but the area of the Western Mediterranean is many times greater. The height which I observed in the Western Mediterranean in a moderate gale (speed of wind estimated by the captain of the vessel at 30 miles per hour) is the same as that recorded for gales of exceptional severity upon Lake Superior, in which the velocity of the wind would not be less than 53 miles an hour. The height, therefore, attained by the largest waves in very severe storms in the Western Mediterranean must be greater. The storms of the Gulf of Lions situated to the westward of my place of observation are notorious for their severity and for the dangerous sea which rises. Admiral W. H. Smyth, in his book upon the Mediterranean,[1] writes that in the worst weather in the Gulf of Lions the waves attain a height which cannot be much less than 30 feet. Perhaps we may interpret this as meaning that they cannot be less than 27 to 28 feet.

Waves in the China Sea

The China Sea is a body of water lying between the mainland of Asia and the open Pacific, from

[1] Quoted by Cialdi, "*Moto Ondoso del Mare.*"

which it is screened by the Philippine Archipelago and other islands. The uninterrupted expanses of water are greater than in the Western Mediterranean. The following observations were made by the late Lieutenant Paris, of the French Navy, whose careful methods of work will be described later. Off Cape Varella, in a violent storm from the north-east which lasted several days, the highest wave was 21.3 feet and the average wave-length 328 feet. The sea-room to windward was about 750 statute or 650 geographical miles. Thus the difference in the sizes of waves in great lakes and in the much larger semi-enclosed seas respectively is less than we should have expected from the observed difference between their size in the smaller and in the larger lakes. We find, however, a great increase when we go from the semi-enclosed seas to the open oceans.[1]

[1] In the Caribbean Sea also, where I have made five voyages, the waves are not quite like those of the open ocean. Between Colon and Kingston they have a clear run of more than 500 nautical miles in the direction of the prevailing NE. wind, which blows strongly. The waves, which I have seen attain a height of above 20 feet during ordinary strong Trade winds, remind one more of those of the Mediterranean than of the Atlantic, and there is an absence of the long swell accompanying the rough sea which is characteristic of the open ocean.

CHAPTER II

Observations of waves on the North Atlantic—Conclusion as to height of North Atlantic waves—Waves on the North Pacific—The effective length of fetch of strong winds on the North Atlantic Ocean—The numerical relation between the length of fetch of wind and height of storm-waves—Waves on the South Atlantic and Southern Indian Oceans—Waves on the South Pacific Ocean—The discrepancy between wave-lengths determined respectively by simultaneous and by successive observation of wave-crests.

Waves on the North Atlantic Ocean

I NOW pass on to the records of storm-waves on the North Atlantic Ocean. One of the best is that of the Rev. William Scoresby,[1] which I give almost in his own words.

The height of the waves was recorded on the east-bound voyage from America to England on board the S.S. *Hibernia*. The construction of the ship afforded several platforms of known elevation above the water-line. On March 5, 1848, the ship

[1] British Association Meeting of 1850, Report, published 1851, Part II., pp. 26–31.

was in latitude 51° N. and longitude 38° 50′ W., the wind about WSW., and the ship's course true N. 52° E. By sunset of the previous day the wind was blowing a hard gale, which continued with heavy squalls during the night, so that all sail was taken in except a storm stay-sail forward. The barometer, which had stood at 29.50 inches at 8 p.m. on the previous day, had fallen to 28.30 inches by 10 a.m. on the 5th. On the afternoon of this day Dr. Scoresby took up his post of observation on the saloon deck, which gave an elevation of the eye 23 feet 3 inches above the water-line. He found, however, that every approaching wave intercepted the horizon, so that from this position he could decide little except that the average height, reckoned from trough to crest, was more than 24 feet. He therefore ventured upon the paddle-box, which was about 7 feet higher, giving an eye elevation of 30 feet 3 inches. This level was well maintained during the moments of actual observation, because the whole of the ship's length (220 feet) was clear within the trough of the wave when the next following crest was at its greatest apparent height, and the ship at these moments was on an even keel. From this position quite one half of the waves which overtook and passed the ship were above the level of the observer's eye. Sometimes a crest extending in a ridge 100 yards long would be from 2° to 3° above the invisible horizon. This Dr. Scoresby says would give a height from trough to crest of more than 40 feet, but I confess I regard this rather as a guess than a measurement. Sometimes, he says, the crossing of two wave-crests would send up a sharp peak of water to a height which he believed to be 50 or 55 feet, or the crest of a breaking wave would shoot up to a similar height. The average height of the waves during the observations on March 5th was more than 30 feet.

On the following day, when, the wind being less violent, the waves had subsided to an average height of 26 feet and were more regular, Dr. Scoresby determined the wave-length in the following indirect manner. The waves overtook the ship every 16.5 seconds and each wave took 6 seconds to run the whole 220 feet of the ship's length. Then the distance between two succeeding wave-crests as thus observed was:

$$220 \times \frac{16 \cdot 5}{6} = 605 \text{ feet};$$

but the ship was not running in exactly the same direction as the waves, and a line from crest to crest measured at right angles would of course be shorter. Making due allowance for the observed angle, the true wave-length was determined to be 560 feet.

So far Dr. Scoresby.

I proceed to consider the position of his vessel at sea so as to be able to compare the sea-room with that possible on Lake Superior, which we have stated to be (at Duluth) 259 nautical miles.

At noon on March 5th, the day when the waves were highest, the vessel was about 600 geographical miles from the coast of Newfoundland, the direction from which the wind blew, and by 4 o'clock in the afternoon 36 miles farther from this, the nearest shore. At noon on the 6th the distance from shore was about 800 geographical miles. If the highest waves were measured at 4 p.m. on the 5th, the ship had been running twenty hours in a hard gale, and was 180 geographical miles from the point where the full force of the gale first struck her. The cyclone was, presumably, travelling in the same general direction as the ship, but how close to the shore the westerly wind first attained the force of a gale we do not know. This much is certain, that where the waves attained an average height of more than 30 feet, and an occasional maximum estimated at more than 40, the sea-room or stretch of water to windward[1] was 600 geographical miles or more, as compared with the 259 geographical miles which is the maximum amount of sea-room possible upon Lake Superior, where we have accepted $22\frac{1}{2}$ feet as the height of waves in exceptionally severe storms.

The wave-length of 560 feet[2] was measured on the Atlantic with a sea-room of 800 geographical miles as compared with the 300 feet of Lake Superior with a possible sea-room of 259 geographical miles.

The length of the waves on March 6th was 21.6 times as great as the height, but on the previous day they must have been steeper.

We will next consider the case of another strong gale in the North Atlantic with sea-room of at least 1,000 instead of 600 geographical miles, in which we shall find that the waves are of about the same height as in the last case.

The waves in question were observed by myself on December 7, 1900, when outward bound from Liverpool to Boston by the Cunard S.S. *Ivernia.*

[1] The "room" which concerns a navigator is more often that to leeward, but the expression for space to windward is useful for our purpose.

[2] From the building line in Bond Street to the front of the Royal Geographical Society's House, 1, Savile Row, is the length of a 10-second wave, 512 feet.

A STRONG GALE IN THE NORTH ATLANTIC.

Leaving Queenstown on the morning of the 5th, we met a rather heavy swell on our westerly course, which continued and somewhat increased during the 6th. We drove into a strong gale that night, and the highest waves which I saw during the voyage were on the morning of the 7th. The force of the wind on that day was logged as 9 on Beaufort's scale of 0-12, the number 9 being called "a strong gale." We continued to drive through a gale during the whole of the 7th, 8th, and 9th, the winds varying from S. by W. on the morning of the 7th to WNW., always therefore producing a head sea, at first on the port, afterwards on the starboard. The morning of the 7th (bar. 29.15 inches) was the only time during the three days when the waves were "running true"—*i.e.*, in long parallel ridges exactly at right angles to the wind, of which ridges six or seven were simultaneously visible when looking upwind from the weather side of the ship. There was no long, flat swell noticeable, neither were there minor waves of such prominence as to distract attention from the principal waves. In the course of eleven voyages across the Atlantic this is the only occasion on which I have seen this "regular sea" during a storm, and the waves were the highest which I have ever observed in a storm. Our noon position was N. 50° 56′, W. 25° 33′, so that the distance from the Newfoundland Banks was about 1,000 geographical miles. This was the direction in which we were steaming and apparently the direction from which the bad weather was coming. The wind, however, came from a direction in which there was no land for 2,000 geographical miles. I was able to judge the height of the waves more readily than usual on account of several favourable circumstances. The ship, though pitching, did not roll, being heeled over to starboard at a moderate angle, which did not vary. Stationing myself amidships, I was subject to neither pitching nor rolling, but merely to a lift and fall as each of the large waves passed beneath us. The two promenade decks afforded platforms which happened to be at just the right altitudes for judging the height of the usual, and of the maximum, waves respectively. The altitude of these decks above the water line of the ship I obtained from the scale section of the ship in charge of the chief engineer. The heeling over of the ship was measured, and its amount allowed for, on the assumption that the height of the deck above the water was reduced, on the lee side, to the full extent possible. The height of the waves is recorded as equal to the height of the eye above the ship's water-line, where they just topped

HEAVY SWELL IN THE NORTH ATLANTIC.

the horizon, nothing being added for the small amount by which they actually exceeded the height of the eye. Thus, when observing on the lower deck, I found that the waves commonly attained 29 feet, and from the upper deck that they occasionally attained 43 feet. My lower platform was about the same altitude as Dr. Scoresby's highest position, and my estimate of the height of the ordinary waves is about the same as his. I had the advantage, however, of a second and higher platform, which brought me on a level with the highest waves. Their height as measured by me from this point of vantage is practically the same as that guessed by Dr. Scoresby from his lower platform. The force of the wind was about the same in both cases, his determination with 600 geographical miles sea-room, mine with 1,000 miles.

Next day, December 8, 1900, the wind had shifted to WNW. with force 8 (a "fresh gale"); the waves were irregular and not so high, and again on the 9th, with wind SW. of the same strength, there was an irregular sea with no very high waves, though they were magnificent from the tumult of their headlong rush and the white fury of the broken water. The sea was, indeed, covered with spume and veiled in spindrift. A small schooner sighted in the afternoon was running before the storm under a minimum of sail, and rolling very heavily. From on board this vessel such waves would tower above the horizon, but none were as high as 30 feet. The position of our ship on the 9th was not far S. and E. of that of Dr. Scoresby's ship when he measured the 560-feet wave-length.

Although the higher platform of my larger vessel gave me an advantage for the measurement of the highest waves, her great length, and the structure of the upper works usual on modern liners, made it very difficult for me, unassisted, to measure wave-length. I have found the same difficulty every time I have been at sea, as I have always voyaged in ships measuring from nearly 500 to 600 feet in length. It has usually happened that when there were large regular waves their course made a considerable angle with that of the ship, and even when the waves ran more nearly in our own direction, it was generally impossible for me to watch the wave-crest during the whole of its passage along the length of the ship. I have, therefore, been generally reduced to judging the wave-length in terms of the known length of the ship from the simultaneous position of two crests. The length of the *Ivernia* is 600 feet, and the regular waves which we encountered in the strong gale of December 7th I judged by the above method to be about 350 feet in length.

I have never yet seen storm-waves on the North Atlantic in which the distance between the wave-crests, viewed simultaneously, appeared to me nearly as long as the 600-feet ships on which I have voyaged, nor, indeed, any which appeared more than 400 feet in length. This was the apparent distance between crests during a heavy swell without wind which I observed from the Red Star S.S. *Vaterland* in March, 1901, east-bound in N. Lat. 48° 30′, W. Long. 21° 40′.

The second, and latest, opportunity which I have had of measuring very large waves on the North Atlantic was on board the Atlantic Transport Company's S.S. *Minnehaha*, east-bound from New York to Southampton, on February 9, 1907, in N. Lat. 48° 54′, W. Long. 18° 20′. There was only a moderate breeze from NW., but a huge north-westerly swell came upon us at about 45° abaft the beam. The vessel did not pitch, her slow and stately rolling motion was perfectly rhythmical and regular, and in the absence of strong wind observation was unusually easy. It was evident from the great height of the swell that we were only just outside the storm area, and this conclusion was confirmed by a wireless message received during the day from the White Star S.S. *Cedric* to the northward of us reporting that she was in a strong NW. gale. Standing on the lower promenade deck, one long ridge after another obscured a considerable arc of the horizon after passing beneath the ship, and continued so to obscure it when at a distance estimated at 400 to 600 feet from us. I allowed 2 feet as a minimum estimate for the excess of height above my eye, based on an observation made a short time before. The observation was simply this, that when sitting in my deck chair I had seen a wave similarly obscure the horizon, and on my rising at once, the horizon remained obscured. The increase in the elevation of eye upon rising was found afterwards to be 2 feet.

The roll of the ship at the time of the obscuration of the leeward horizon was in each case to the weather side, so that the deck on the lee side was tilted upwards. The amount of the tilt was measured for several rolls, which were quite regular, and assuming that the full amount ought to be added to the deck height, I obtained 2 feet so to add. I was standing during the observations, and my eye-height is 5 feet 9 inches, or say 5½ feet, so that there is altogether 9½ feet to add to the height of the deck. This, measured with a heavy

WAVES AND SWELL IN THE NORTH ATLANTIC.

rope hung over the lee side, I found to vary with the oscillations of the ship and of the water from 29½ to 33½ feet, giving an average of 31½ feet for smooth water. Two days later, with lighter bunkers, the height above the smooth water of the Solent was found by the rope to be 32½ feet.

Taking, therefore, the height of the deck at the time of observation as 31½ feet, the height of the waves which repeatedly passed us was:

Height of deck	31½ feet
Added for roll	2 "
Height of eye above deck	5½ "
Height of wave above the eye (at least) ...	2 "
Wave height (at least)	41 feet.

Whilst this is 2 feet less than that determined for the highest waves during the strong gale of December 7, 1900, there was much less variation in size from one wave to another, and the average height in this north-westerly swell was no doubt quite as great as that during the strong southerly gale.

The sea-room on February 9, 1907, reckoned from the coast of Greenland—the direction of the wind—was about 1,100 geographical miles, and from the Newfoundland Banks to the westward about 1,200.

Conclusion as to Height of North Atlantic Waves

Thus concordant observations indicate that anywhere in the North Atlantic with sea-room of from 600 up to certainly 1,000 and perhaps 2,000 miles the height of the large waves during ordinary strong gales is practically constant, being not less than 43 feet.[1]

With regard to the height which is momentarily attained by peaks of water shooting upwards where waves cross, the late Lord Kelvin informed me that he had measured one 60 feet high, and this measurement confirms the concordant guesses of several officers on North Atlantic liners whom I have consulted on the subject. I have not myself seen anything nearly so high.

Accounts not infrequently appear in the newspapers of some great wave encountered by the fast Atlantic liners. These are sometimes reported as 80, 90, and even 100 feet high. This height invariably relates to the altitude above the flotation line of the superstructures which have been deluged with water. This is not, properly speaking, the height of a wave, but merely the height to which a body of water is thrown when a wave breaks on board. This increases with the speed of the

[1] See Note on p. 138.

ship, which dips her bows into the rising billow in a head sea. The recorded heights also tend to increase as the ships are built of larger dimensions, on account of the fact that the greater height of the navigation bridge and wheel-house allows the attainment of a greater altitude to be recorded with certainty. The wheel-house of the *Lusitania*, *e.g.*, is 80 feet, or rather more, above the flotation line.

Waves on the North Pacific Ocean

The North Pacific Ocean has a breadth of open and deep sea about twice as great as that of the North Atlantic. The passage from Victoria, B.C., to Yokohama is about 4,000 geographical miles, as compared with the 3,000 from Liverpool to New York. This route is traversed by a number of liners similar to the medium-sized Atlantic liners. I made this passage once, east-bound from Yokohama to Seattle, in fair weather, when we only encountered a moderate swell similar to that met with in similar weather in the same latitudes on the Atlantic. The great circle course which is followed took us as far north as Lat. 49° 40′. I had opportunities during this long voyage of collecting opinions upon the size of the waves on this route as compared with those of the North Atlantic and of the Southern Ocean from seamen who knew all three. The late

Dr. Elgar, F.R.S., designer of the *Campania,* who was also a passenger, gave his views. There was a complete consensus of opinion—

First, that the type of storm was the same as on the North Atlantic routes.

Second, that the storm-waves on the Pacific route were certainly not higher than those on the Atlantic, and I did not gather that they were any longer. They were said to be as irregular as those of the North Atlantic and not to " run true " as the waves do in the steadier winds of the Southern Ocean, a circumstance which was attributed to the storm being generally of the rotatory character, with a fairly rapid change in the direction of the wind. I conclude from this evidence that the greater size of the ocean does not in this case lead to the development of greater storm-waves than those of the North Atlantic.

Thus I have not found in northern latitudes any increase of height of storm-waves beyond a distance of 600 geographical miles from the windward shore. Nevertheless the size of waves observed by Scoresby is not nearly equalled in enclosed seas of 500-700 miles in breadth.

I attribute the difference to a smaller size of cyclonic systems on the semi-enclosed seas.[1]

[1] *Cf.* A. Buchan, " Meteorology," " Encyclopædia Britannica," 9th edition.

On the Effective Length of Fetch of Strong Winds on the North Atlantic Ocean

The volume of charts illustrating the weather in the North Atlantic from December 18, 1898, to February 15, 1899,[1] provides detailed and reliable information as to the effective length of fetch of winds in that ocean. The storms were of unusual strength and persistence, so that the charts give us maximum values. The positions and distances stated below are measured from the charts. At noon, January 1, 1899, a west wind of force 7-8 of Beaufort's scale and upwards (*i.e.*, in no place less than a moderate gale) is shown to obtain from N. 49°, W. 40° to N. 49°, W. 60°, a distance of 1,300 geographical miles or rather more. But, in order that the waves at the lee end should be reinforced by those at the weather end of the strip, time must be allowed for the travel of the waves. Waves of about 8 seconds period would be prevalent in such winds, and we will consider their movement. Their speed is $8 \times 3 = 24$ knots, and even when going as forced waves before the wind they will only travel 576 geographical miles in 24 hours. Now, an examination of the charts for Decem-

[1] Charts illustrating weather of the North Atlantic Ocean in the winter of 1898–9, Met. Council, 1901.

ber 31st and for January 2nd shows that on neither day was there so long a strip of water simultaneously subject to west wind of force 7-8 as on January 1st. Therefore the apparent length of fetch on that day never became effective. But we see on comparing the chart of December 31st with that of January 1st that a strip of 550 geographical miles was continuously subject to west wind of force 7-8 for 24 hours, and towards the end of this period this was the effective length of fetch of the wind for 8-second waves, and for any swifter waves which the force of the wind may have been capable of producing.

At noon on January 10, 1899, winds of Beaufort force 7-8 with direction a little W. of N. prevailed from N. 47°, W. 46° to N. 48°, W. 32°, a distance of 600 geographical miles. On the previous day (January 9th) at noon the wind was blowing in the same direction between the same two positions, with a force of 9-12, so that for 24 hours there were winds of constant direction, with a force varying from a moderate gale to a hurricane, simultaneously and continuously affecting the water over a stretch of 600 geographical miles. Towards the end of the period, therefore, there was an effective length of fetch of wind of 600 geographical miles for all waves of rather more than 8 seconds period.

UNDULATING HORIZON OF A ROUGH SEA.

Throughout the whole of the nine weeks of exceptionally stormy weather which is covered by these charts I cannot be sure of any greater effective length of fetch of wind than 600 geographical, or 700 statute, miles. This is the wave-making length of wind-fetch for the North Atlantic which we have to compare with the 259 geographical or 289 statute miles of Lake Superior. The wave-making effect of a strip of wind of 600 geographical (700 statute) miles long on the mid-Atlantic is, however, increased by the swell which is always entering at the weather end. This result agrees with the conclusion already arrived at that Scoresby observed, at 600 geographical miles from the windward shore, waves of the greatest height producible in the Atlantic by the then force of wind.

The Numerical Relation between Length of Fetch of Wind and Height of Storm-waves

Thomas Stevenson's empirical formula (height of wave in feet = 1.5 × square root of length of fetch in geographical miles) was shown by him to apply to distances of rather more than 100 geographical miles. Colonel Gaillard observed waves 23 feet high in the Duluth Canal with a length of fetch of 259 nautical miles, the height calculated from Stevenson's formula being 24.1 feet. The same formula gives 36.75 feet for 600 geographical miles from the windward shore, which is in fair agreement with Scoresby's observations on March 5, 1848 (see *ante*, p. 42).

Waves on the South Atlantic and Southern Indian Oceans

Sailors agree that storm-waves are seen in their fullest and most typical development in those Southern latitudes where the ocean uninterruptedly encircles the globe. They are observed from ships which go round the Cape of Good Hope, and by those which go round Cape Horn. I proceed to the observations made by the late Lieutenant Paris,[1] of the French Navy, in 1867, when proceeding by the corvette *Dupleix* to the China station via the Cape of Good Hope. The *Dupleix* was a sailing vessel with auxiliary steam. She ran before a prolonged westerly gale during the last days of October, 1867, having passed the Agulhas Bank, but being still west of the Island of St. Paul. The vessel seems, therefore, to have been somewhere between 40° and 80° E. Long. and about 40° S. Lat. After this storm the vessel proceeded northwards under steam through the calms of Capricorn,

[1] See *Revue Maritime et Coloniale*, vol. xxxi. (1870), pp. 111–127, "Observations sur l'État de la Mer."

accompanied by a swell from the south-west. Lieutenant Paris made regular observations of waves during the whole of this voyage, and when cruising in the seas of China and Japan, but his opportunities of measuring large ocean waves occurred only in the southern ocean, and principally during the storm above referred to. For obtaining data as to the size of full-grown storm-waves from his valuable paper, we are, in fact, almost restricted to a single day's observations, but the value of this day's work is greatly enhanced by his daily practice in observing. His method, as he explicitly states, is that of Dr. Scoresby, the wave-lengths being usually obtained by noting the time occupied by the wave in running the length of the ship combined with the interval elapsing between the arrival of the waves. The height he calculates as equal to that of the eye when the wave just obscures the horizon; but his observations in this respect are superior to Dr. Scoresby's, for, by nimbly running up or down the shrouds, he got on a level with each succeeding wave, and was not reduced to Scoresby's expedient of guessing the height above him of the largest waves. His results are as follows. On October 25th, 1867, between the Cape of Good Hope and the Islands of St. Paul and Amsterdam, during a strong gale from the north-west with violent snow squalls, he measured at different times of the day 30 waves which averaged 29.5 feet in height, and of these 6 succeeded one another in a procession, all the members of which were of equal height, viz., 37.7 feet (11.5 metres). Later in the day he saw waves which he says were "certainly higher" than these, but he was not at the time so placed as to be able to measure them. Their height, we may safely conclude, was not less than 40 feet and probably a little more. Several sailors on board who had been much at sea had never seen waves so high. They occurred on what appears to have been the fourth day of the gale, but the narrative is not quite clear upon this point.

It will be noticed that both in average and extreme height the results are practically the same as were obtained during strong gales in the North Atlantic by Scoresby on March 5, 1848, and by myself on December 7, 1900.

The waves were, however, much longer in the Southern Ocean, the greatest average on any day being 771 feet, with not a few of 900, and several waves surpassing 1,312 feet (400 metres) in length. Scoresby, measuring in the same indirect way, found the Atlantic waves 560 feet long.

Although at the outset of our discussion of the relation between the size of waves and the size of the basin in which they were formed, I used either observed lengths, or lengths calculated from the period, according to which were available, I find that in observations from shipboard in the open ocean there is in this matter a troublesome discrepancy. Most of the "wave-lengths" given in published records such as those of Scoresby and Paris were not really observed as an apparent distance separating two ridges of water viewed simultaneously, but are deduced by calculation from observed speeds. The speed is obtained in the way described by Dr. Scoresby, viz., the observation of the time taken by a wave-crest to run the length of the ship, combined with the interval between the arrival of two wave-crests, the speed of the ship being known. When the ship is broadside on to the waves their apparent period should enable one to calculate at once the wave-length. I found, however, when observing at sea, that the length so calculated was much greater than the apparent distance between successive convexities of the water's surface. I have also found that many officers on the Atlantic liners disclaim ever having witnessed in the North Atlantic waves of the great lengths which are measured indirectly by systematic observers from the observed speeds of, and the interval of time between, successive waves. The discrepancy I suppose to be in some way connected with the fact that in a storm there are always waves of different length and speed running in the same direction. The waves made by the ship, which are stationary with respect to the ship herself, also I think produce a confusing effect on the direct method of estimation by increasing the height of the progressive waves at certain definite positions. I do not think it desirable to set aside either mode of observation, and in what follows I shall record both. The reader will in consequence find that, while the records of heights provide consistent numbers which are comparatively easy to interpret, the records of length are more confused.

Lieutenant Paris remarks of the great series of six waves above described that, as they passed, they left the ship, which was 230 feet long, in a valley "a cable's length" (600 feet) across.

The following is a case of a great wave-length recorded by direct observation in the same part of the ocean, viz., on the route from the Cape of Good Hope to Australia. Major Leonard Darwin, who communicated the facts to me, was on this voyage in a vessel 400 feet long, when they fell in with a gale of such unusual severity that the

Captain went twelve hours out of his course in order to partly avoid its fury. Major Darwin made a special effort to judge the distance separating crest from crest of the great rollers, and came to the conclusion that it was three times as great as the ship's length—*i.e.*, 1,200 feet. Thus we see that if we compare the wave-lengths, calculated from the velocity of the waves, as observed between the Cape of Good Hope and Australia with those obtained by the same process in the North Atlantic, the Southern Ocean has much the longer waves, and, again, if we compare the eye-estimated length in the Southern Ocean with that in the North Atlantic, the Southern Ocean has also much the longer waves.

The following observations by Captain Hugh F. David, of the White Star S.S. *Corinthic*,[1] were made during August, 1907, somewhere between S. Lat. 45° 30′, E. Long. 61° and S. Lat. 46° 45′, E. Long. 98° 25′. This is between the Island of St. Paul and Kerguelen Island, and about 600 geographical miles farther south than the position where Lieutenant Paris made the observations above described. The direction of the wind was westerly, and its greatest force was logged as 9,

[1] Letter to Captain Campbell Hepworth, R.N.R., of the Meteorological Office, and log of the *Corinthic*.

which on the Beaufort scale of 0-12, is equivalent to a wind-velocity of 44 statute or 38.2 geographical miles per hour, and is termed "a strong gale." An interesting photograph was taken at the after-end of the promenade deck, with camera 26 feet above the sea level, showing a neighbouring wave following the ship and eclipsing the distant horizon. Captain David writes:

"With regard to the lengths and heights of the waves at the time of the photograph, I did take quite a few observations, more particularly of the heights, which ranged from 38 to 45 feet, though I have a vivid recollection of one which I think was quite 50 feet in height. Standing on bridge at 50 feet above sea level, the crest of this wave appeared level with the eyes of jigger rigging just before ship's stern commenced to rise. The height of rigging from the horizontal line drawn from bridge rail to jiggermast taken from scale slightly exceeds 50 feet. This was, of course, an exceptional wave, and I felt quite glad when it passed without doing any damage. Referring to their length from crest to crest, I would not be quite so definite, though an average would be about 600 to 750 feet during the worst part of the storm and indeed afterwards." (The length of the *Corinthic* is 500 feet.)

In the absence of any statement to the contrary it may be safely concluded that the wave-length was judged by eye, not determined by indirect measurements as in the cases of Paris and Scoresby, eye estimation of the distance between two crests simultaneously observed being the almost universal practice of officers on the bridge. Thus this length for Southern (Indian) Ocean of 600-750 feet should be compared with my eye estimate of 350-400 feet for similar weather in the North Atlantic, and not with Scoresby's indirect measurement there of a length of 560 feet.

Captain Percy Howe, who has voyaged on the same route, informs me that between the Cape of Good Hope and Adelaide he was in 1907 subject to a gale of 21 days' duration, from July 15th to August 5th, much the most prolonged which he has ever experienced. During the most violent parts of the storm the waves which passed the ship obscured his horizon when the ship was on an even keel. His eye-height on the bridge of the *Owestry Grange* was 45 feet, so that the waves exceeded this height. The ship's length was 480 feet, and she was wholly within the trough of the waves, the length of which he estimates at 750 feet. These estimates, which are almost the same as Captain David's, are for a part of the same series of exceptional storms.

Waves on the South Pacific Ocean

Leaving now that part of the Southern Ocean which is on the routes from the Cape of Good Hope to Australia and New Zealand, we will examine records from the Cape Horn route from New Zealand to Europe, which touches higher latitudes.

The following observations for height were given me by Mr. G. T. Ogilvie. He came home (eastbound) by this route in 1880 on a 1,300-ton ship, with a length of 230 feet. Whenever it blew hard he used to get into the mizzen rigging and sight on to the horizon from various heights. Near Cape Horn, and therefore more than 53° S. of the Equator, in a full gale blowing from about SW., he estimated the highest wave as 2 feet above his plane of observation, which, on the Captain's estimate, was then 40 feet above the water-line, making a total wave-height of 42 feet. Waves 30 feet high were comparatively common. He thought he saw one or two rollers not less than 45 feet in height from trough to crest, and possibly 48 feet, but attaches little weight to the figures for the altitude of a wave apparently so far above the line of sight.

The following observations by the Hon. Ralph

Abercromby[1] relate to waves observed in the South Pacific Ocean on a voyage between New Zealand and Cape Horn on S.S. *Tongariro* in 1885. On July 16th the ship was in S. Lat. 55°, W. Long. 105°, in a hard gale from SW. The waves were the largest seen on the voyage. For the measurement of their height he used a $4\frac{1}{2}$-inch aneroid barometer with a very open scale divided to .01 inch. He found (on the assumption that a difference in .001 inch in the aneroid reading was equivalent to a change of 1 foot in level) that in passing from trough to crest the greatest lift experienced by the aneroid in the cabin was 40 feet. This was a solitary instance. The next greatest was 30 feet. Now, on a previous day, he had found by measurement with a piece of string that, when the wave-crest passed the cabin, the porthole was 6 feet nearer the water than it was at the trough of the wave. Assuming the same difference to hold during the day of heavier sea, he adds 6 feet to the lift of 40 feet in order to obtain the total height of the greatest wave, which he therefore considers to have been 46 feet. He reckons the liability to error of the aneroid reading at 2 to 2.5 feet, and that of the measurement

[1] *Phil. Mag.*, April, 1888 (vol. xxv., 5th series), "Observations on the Height, Length, and Velocity of Ocean Waves."

of water-level by the string at not less than 2 feet either way. Thus, his determination of a single wave-height of 46 feet may really be due to a wave of anything from 41½ feet to 50½ feet in height, and therefore, as is the case with so many other measurements in storms at sea, can only be taken actually to establish a wave-height of a little more than 40 feet. Dr. G. Schott, using a sensitive aneroid with microscopic reading, recorded a maximum wave-height of 39.4 feet in the South (Atlantic) Ocean.

On the Discrepancy between Wave-lengths determined respectively by Simultaneous and by Successive Observation of Wave-crests

On March 15, 1903, I was on the S.S. *Hitachi*, of the Nippon Yusen Kaisha, in N. Lat. 28° 26′, E. Long. 125° 53′, bound for Kobe, from Hongkong. The position is in the East China Sea, which is here only partially screened from the open Pacific by the Loo-choo Islands. We encountered in the afternoon a heavy northerly swell, which met the ship at an angle estimated by eye at 45°. One crest was at the stern when the next following was at the bow, and, knowing the length of the ship, the true distance from crest to crest, reckoned at right angles to the course of the waves, was known to be 280 feet. But the interval between the arrival of the waves was $8\frac{1}{2}$ seconds, and, as the vessel was travelling in a direction somewhat opposed to the direction of the waves, the true wave-period must have been somewhat greater. An $8\frac{1}{2}$-seconds wave has a length in deep water of 370 feet and a 9-seconds wave of 415 feet.

Assuming the determination of the period to be fairly accurate, as the observation is an easy one, and the application of the mathematical formula to be valid, as there is every reason to suppose, we must seek some reason why the apparent wave-length should be quite 90 feet less than the true.

Two possibilities suggest themselves. The first is that minor sea-waves are noticed in the simultaneous observations of wave-crests, but are passed over by the eye when watching the progress of the more rapidly moving crests of the principal sea-waves.

The second possibility is that the shortening of apparent wave-length was due to the increased height of the sea-waves in the vicinity of the bow and the stern of the vessel. A large vessel proceeding at a fair speed—in the above case a vessel of about 6,400 tons going at 12 knots—produces a short, steep wave, several feet high, at the bow, and a similar one at the stern. In smooth water these are stationary relatively to the ship, and have a constant height. In a slight head sea, however, the stationary bow-wave is replaced by an intermittent wave, rising up, when the sea-wave meets the bow, and subsiding at the trough of the sea-waves. In a heavy head sea the ship's own bow-wave becomes inconspicuous, but, nevertheless, contributes as much as before to the total height of the sea-waves as they reach the bow and the stern. Now, looking aft, the steeper ship-wave will maintain the apparent crest of the flatter sea-wave for some distance after the crest of the true sea-wave has passed. Conversely, looking forward, the steep bow-wave will cause an anticipation of the true crest of the advancing, flatter sea-wave. Consequently the above measurement of wave-length by simultaneous position of crests along the ship's side was too small by twice the distance through which the steeper ship-wave shifted the position of the combined wave-crest.[1]

Where the sea waves are large and regular and long, and the ship small and slow, this error is least. With a moderate sea and a large and swift ship the error is greatest.

Officers of the Atlantic liners generally estimate

[1] The presence of ship's waves need not affect the determination of wave-length from observed velocity, for the interval between the arrival of a sea-wave at stern and bow is the same as if there were no ship-wave.

wave-length by the position of crests with relation to the bow and stern of the vessel. Thus, when sailing by the Allan liner *Tunisian*, in 1901, the chief officer informed me that in a storm in the Atlantic the ship generally "took three waves," which means that when one crest is at the bow and another at the stern there would be a third crest between. In other words, there would be two sea-waves to the ship's length. The *Tunisian* is 520 feet long, which would make the apparent wave-length 260 feet.

In my endeavours to get at the truth about the dimensions of sea-waves, I have done three things: first, made measurements myself; second, examined the records of measurements made by others; third, consulted officers on all ships by which I have travelled as to what their experience leads them to suppose the height and length of waves to be. Now, the officers of the Merchant Service have far more experience of weather in the open oceans than most naval officers, for ships of war keep mostly to the vicinity of land. *A fortiori* their experience is far greater than that of landsmen such as myself. On the other hand, those to whom I have spoken on the subject have not actually made measurements. The result of my three lines of inquiry is as follows:

As regards the height of waves, the general opinion of the officers of the Merchant Service accords with remarkable closeness with the measurements which have been made by Dr. Scoresby, Lieutenant Paris, Captain David, and Mr. Ogilvie. My own measurements confirm both, as far as the heights of waves in the North Atlantic are concerned. "About 40 feet" for the fairly frequent larger waves in an ordinary North Atlantic storm is the general verdict of the officers on the liners, and they are generally prepared to concede a few feet more for waves in exceptional storms, especially in the region of westerly winds in the Southern Ocean. From the records discussed in detail above I find that the larger waves in ordinary North Atlantic storms attain 43 feet and in exceptional storms both here and in the South Indian Ocean attain, and perhaps surpass, 45 feet. The possibility of an occasional peak of water shooting up to a height of 60 feet before breaking is sometimes admitted, but those whom I have consulted generally feel that there is little to be gained by guessing at the figures applicable to such circumstances when they have had no reliable standard of measurement.

In the matter of wave-length in the North Atlantic, however, I find the general opinion of officers on the liners to be that 600 feet would be an enormous wave-length, and, if intended as an average, and not merely the distance between a single pair of crests in a confused sea, would not be met with there in ordinary storms.

Such a sea, in which a large ship of 500 feet long running directly before the wind is left, time after time, within the trough of the wave, they have only witnessed in the Southern Ocean, particularly in the part east of the Cape of Good Hope, where the sea is more regular and is probably longer than that near Cape Horn, though perhaps not higher.

Thus, it is only in the Southern Ocean, particularly in the eastern parts, where the waves are not only large but regular, that the officers' estimate of wave-length agrees with the measurements from speed and periodic time.

I have not yet traversed the Southern Ocean, but in my efforts to judge wave-length from on board ship in the Irish Channel, the Mediterranean, East China Sea, Caribbean, North Pacific, and North Atlantic I almost despaired of getting any results worth recording on account of the discrepancies above described. It seems as if the measurements from velocity and period were a nearer representation of the natural state of the sea than those gained by officers from their experience on the bridge. Yet the latter must not be lightly dismissed, and more attention should be given to unravelling this part of the subject. My explanation of the systematic effect of the ship's waves to shorten the apparent wave-length I believe to be an important part of the whole explanation, but it may not be the sole cause.

It is possible that the observed elevation of the wave-crest above the ship's flotation line is sometimes increased on account of the presence of a ship-wave tending to make the recorded heights of waves too great, especially when observed from large, fast ships.

On the other hand, a large vessel, among waves shorter than herself, neither rises to the crests nor sinks to the troughs, so that in observations such as my own on the *Minnehaha* and the *Ivernia* the recorded height of the wave-crest above the still-water-line of the ship is probably less than the height above the trough.

Thus, these two possible sources of error tend to neutralise each other, and as the heights recorded by eye on large ships agree with those recorded on smaller ones, and both are in accordance with aneroid determinations, as far as these have been carried, we may regard them as probably free from any large systematic error such as that which the ship-wave, and perhaps other superposition, introduces in one of the methods of measuring wave-lengths.

CHAPTER III

The wave-length of the swell which reaches the shore after storms—The height of the swell at sea during storms—The co-existence of waves of different lengths—The give and take between air and water in the development of waves.

The Wave-length of the Swell which reaches the Shore after Storms

WHEN the waves produced upon the deep sea run into water of which the depth is less than 1-4th the wave-length, theory shows that their speed is reduced 6.7 per cent., and when the depth is no more than 1-8th of the wave-length their speed is only 4-10ths of what it was in deep water.[1] This reduction of speed goes on as the wave approaches the shelving shore. Finally, in water of which the depth is only a small fraction of the original wave-length, the wave-speed is the same in all cases, no matter what was the original speed and wave-length in deep water. This progressive

[1] *Vide* Sir G. G. Stokes' "Admiralty Manual," 1886.

change of speed causes the wave-crests to close up, so that the space separating them gets less and less as they approach the shore, but the interval of time between the arrival there of successive crests is unchanged. Consequently, by timing the arrival of a number of breakers, or the passage of a fixed point by a number of waves just before breaking, we know at once the period of these waves, not only as we see them in shallow water, but as they were in water so deep that the wave disturbance did not reach nearly to the bottom. From the period we can calculate the speed in deep water by the mathematical theory of waves, using the formula :

Period (in seconds) = speed of wave in feet per second ÷ $5\frac{1}{8}$

(nearly), or, more roughly :

Period (in seconds) = speed of wave in knots per hour ÷ 3 ;

and we can calculate the wave-length for deep water thus :

Square of period = length of wave ÷ $5\frac{1}{8}$.

The breakers which arrive somewhat irregularly during storms do so at intervals which, as far as I have noticed them, do not differ much from the intervals observed on board ship in the deep sea during storms ; but after storms the period of the breakers is sometimes much greater. Now, this means that their wave-length in deep water was much greater than that observed during storms at sea, and that the speed in deep water of these subsequent waves was also much greater than that of the waves then observed. But when the wind no longer acts upon the water, there is no agent to accelerate the waves. Theoretically, they should travel by gravity at the same speed as that which the action of the wind has induced, or, if there be any change of speed while in deep water, it could only be some very gradual diminution. A real increase in the speed of transmission may be pronounced with confidence to be an impossibility in the absence of any new source of energy.

The only possible explanation, therefore, is that the waves of longer period which come in upon the shore after storms are present, but escape observation, during storms at sea. Not only so, but they have attracted comparatively little attention from on board ship even after storms.

The following observations of the swell, following a westerly storm, were made by myself at Branksome Chine, on the Dorsetshire coast, between Bournemouth and Poole. The storm had been violent and long at Bournemouth, and the weather in the Atlantic exceptionally stormy.

On the morning of December 29, 1898, the wind, now light, having drawn more to the north, the sky was brighter and the weather pleasant, as it generally is here when the wind blows from the north-west after the passing of a storm from the Atlantic. At 11 a.m. an unusually heavy surf came rolling in upon the sandy beach, the waves maintained unbroken almost to the shore by the action of the off-shore breeze, which, at Branksome Chine, always favours the production of a well-formed breaker.

At 11 a.m. came four large breakers at the following intervals, viz.:

22, 18, 20, average 20 seconds.

They were followed by an almost smooth sea; and then, after a short time, came a second series of four large breakers at the following intervals, viz.:

16, 22, 19, average 19 seconds.

At 11.25 a.m. a fine series of seven breakers arrived at the following intervals, viz.:

21, 17, 22, 23, 23, 20, average 21 seconds.

I did not notice any minor waves between the members of the series.

At 11.35 a.m. a set of six breakers came at the following intervals, viz.:

16, 19, 25, 16, 24, average 20 seconds.

And at 11.50 a.m. a set of seven breakers at the following intervals, viz.:

17, 21, 16, 22, 23, 18, average 19.5 seconds.

The general average of the periods of the five sets of waves is 19.9 seconds.

Later in the day large breakers followed one another in continuous succession without the occurrence of any smooth water, and for three-quarters of an hour I noted, watch in hand, a succession of 139 consecutive breakers, occurring at the following intervals, viz. (reading from left to right):

20,	20,	19,	21,	19,	19,	17,	12,	20,	20,	19,	22,
21,	21,	20,	22,	15,	18,	19,	17,	17,	20,	22,	20,
18,	12,	15,	19,	16,	18,	18,	22,	21,	19,	20,	18,
15(?),	15(?),	16,	19,	20,	18,	20,	25,	16,	21,	25,	10,
12,	22,	21,	18,	21,	19,	21,	21,	23,	18,	14,	15,
15,	19,	19,	14,	21,	18,	19,	14,	15,	21,	18,	15,
22,	19,	17,	19,	13,	20,	23,	24,	15,	14,	17,	21,
19,	20,	28(?),	12,	24,	19,	20,	19,	19,	21,	18,	16,
17,	22,	26,	20,	16,	21,	22,	23,	25,	17,	15,	16,
23,	21,	20,	15,	15,	18,	19,	26,	19,	21,	21,	18,
21,	19,	19,	18,	23,	18,	19,	22,	20,	20,	15,	23,
20,	18,	21½,	21½,	21,	20.						

The average interval was 19 seconds, and this determination is accurate to a degree not attained by observations from moving ships. The recorded intervals between the successive breakers probably vary more than the real intervals, because if the observer is too late in his determination of the time of breaking for any wave, he not only makes that interval too long, but the next too short. Thus we see that we had here a fairly uniform series of waves whose average period, 19 seconds, shows that their velocity, when in deep water, was 57 knots, or 66.5 statute miles, per hour, and their average wave-length 1,850 feet.[1]

It was not easy to make exact comparison between the height of these breakers and those which I have seen at Branksome Chine during storms, for the latter break farther out and in deeper water. However, the impression conveyed to the eye is that there is no very great difference between the heights of the breakers above the water in front of them in the two cases. Branksome Chine is sheltered from the west by the promontory called Purbeck Island, so that the waves of westerly gales and the swell which follows are both reduced by change of direction in rounding the promontory. If, however, we recall to mind the numerous references in nautical writings to the great breakers which come in during calm weather upon oceanic islands and other shores directly exposed to the ocean, we shall recognise that their

[1] This is about equal to the distance from Park Lane to Devonshire House, measured along Piccadilly.

height must be of the same order of magnitude as that of the breaking waves of storms.

On December 29, 1898, in N. 47°, W. 19°, waves 45-52 feet high were reported from S.S. *St. Simon*. In absence of details I have not used these in the above records of height of waves, but I take them here to calculate a maximum *length* of storm-wave in the Atlantic during the exceptionally wild weather prevailing at the time of my observation at Branksome. We have already seen that when the length of waves is determined in the manner which gives the highest values (viz., by recording speed and period of arrival from on board ship), maximum waves of 40 feet are associated in the North Atlantic with lengths not more than 600 feet, or fifteen times the height. The corresponding length for a height of 45 feet is 675 feet, and for 52 feet, 780 feet. The latter is a figure probably considerably in excess of the real average wave-length during the storm, for which 600 to 700 feet would be a more likely estimate. Nevertheless, if we took the excessive value of 780 feet for the average length of the storm-waves, this would be less than one-half the average length of the swell observed at a distance.

On February 1, 1899, I recorded at the same place a swell of even longer period. The day was calm, after some days of light winds from north and east. A heavy swell began to come in upon the shore at about 11 a.m., and between 3 and 4 p.m. I timed the arrival of twelve successive breakers, between which the eleven intervals were as follows:

23, 23, 22, 22, 22, 23, 21, 24, 24, 22, 22, average 22·5 seconds.

This is the longest period which I have ever observed for a group of waves. It was noted at the time as a good observation—*i.e.*, the determination of the times was rendered easy by the regularity in the form and progress of the waves. Multiplying the period by three, we obtain with sufficient accuracy the speed in deep water, expressed in knots, which is therefore 67.5. This multiplied by 7-6 gives the speed in statute miles per hour, viz., 78.75. The corresponding wave-length in deep water is 2,594 feet. Although observed in the English Channel, it is an accepted view that such a swell is due to an Atlantic storm. The period is almost twice as great as that (11.7 seconds) recorded by Dr. Scoresby in the storm of March 5-6, 1848, and the speed therefore is likewise nearly twice as great. In a later chapter an account will be given of the probable origin of this set of breakers and of the distances they had travelled (see p. 118).

On September 16, 1900, in fine weather at Branksome Chine, I heard the boom of surf, and, looking from my window, timed a set of well-formed though not large breakers at the following intervals, viz.:

18, 17, 19, 23, 19, 21, average 19·5 seconds.

The following observation of a swell from the Atlantic was made on the north coast of Ireland, near the Giant's Causeway, in the autumn of 1870, by the late Sir G. G. Stokes.[1] One morning a grand surf came rolling in. There had been, some days before, a long succession of heavy gales in the North Atlantic. The period determined from different sets of six or eight waves was 17 seconds. The average difference between the mean periods of the different sets of waves was only about 1-5th of a second. The differences between the periods of individual waves is not recorded, but would, of course, be much greater. Somewhat later the period sank to 16 seconds, in the latish afternoon to 14, and next day to 13. The surf was highest for the 17-second period. During several other summers, when Sir G. G. Stokes spent a month or two on that coast, he never saw anything so striking.

[1] Discussion in Section A, British Association, Dover, 1899, on a paper by the present author.

Some interesting deductions can be made from the above record.

The mean between the period at commencement (17 seconds) and that next day (13 seconds) is 15 seconds; and in 24 hours 5,760 waves of this period would have discharged themselves upon the shore. The length of a 15-second wave is 1,153 feet, so that 5,760 such waves in series would occupy a space of 1,090 geographical miles. The length of the waves at the front of the group was 1,481 feet, and of those at the rear 866 feet. If we suppose the waves travelling freely after the storm, the rate of progress of the group, if reckoned by that of a 15-second wave, would be, not 45, but $22\frac{1}{2}$ knots,[1] so that the advance per 24 hours would be 540 geographical miles, and the interval between the storms and the arrival of the swell was "some days."

The character of the group of waves at the moment when the storm ceased must have been

[1] Vide *Nature*, vol. xvi., 1877, p. 343, for Osborne Reynolds on the relation between group-velocity and wave-velocity in deep water. In deep water a group of trochoidal waves travelling freely under the action of gravity advances at half the speed of the individual waves. If we follow the motion of the first wave of the group, we shall find that it dies out, and the wave behind it has now taken the lead. If, on the other hand, we watch the last wave of the group, we shall soon find that another one has appeared behind it, and the sum total of these

very different from that at the end of their long journey. In the first place, the waves which would have been noticed and measured from ship-board would have comprised none of the length of even the shortest seen at the Giant's Causeway. They would have been the waves from 400 to 600 feet long, with periods of less than 11 seconds, and they could not have arrived at the Giant's Causeway until later. But when they did arrive—as arrive they must—it is evident that they gave rise to no remarkable breakers, for the surf was decreasing

two effects may be represented by the following scheme, in which we take the front wave and place it at the back :—

```
1 2 3 4 5 6 7
  7 1 2 3 4 5 6
    6 7 1 2 3 4 5
      5 6 7 1 2 3 4
        4 5 6 7 1 2 3
          3 4 5 6 7 1 2
            2 3 4 5 6 7 1
              1 2 3 4 5 6 7.
```

In each succeeding horizontal row the individual waves have moved forward two places, but the group has advanced only one. The late J. Scott Russell's early recognition of two wave velocities appears to have been forgotten. He says, in his Report on Waves, B. A. meeting at York, 1844 : "I have found that the motion of propagation of the whole group is different from the apparent motion of wave transmission along the surface; that in the group whose velocity of oscillation is as observed, 3·57 feet per second, each wave having a seeming velocity of 3·57, the whole group moves forward in the direction of transmission with a much slower velocity."

as the period decreased, and observations were discontinued when the period was 13 seconds. Theory shows that when deep-sea waves are left to themselves, the time which they take to flatten out so as to become invisible is proportional to the square of the wave-length.[1] Hence the longer waves are more permanent. Again, waves of all lengths are reduced to the same small speed by the time they break upon the shore; so that waves originally long and swift are shut up, or telescoped, to a much greater extent than the slower ones, and they undergo in the process a correspondingly greater increase in height. On both accounts, therefore, the height of the breakers given by the swifter waves is increased out of all proportion to their original height during the storm.

The Height of the Swell at Sea during Storms

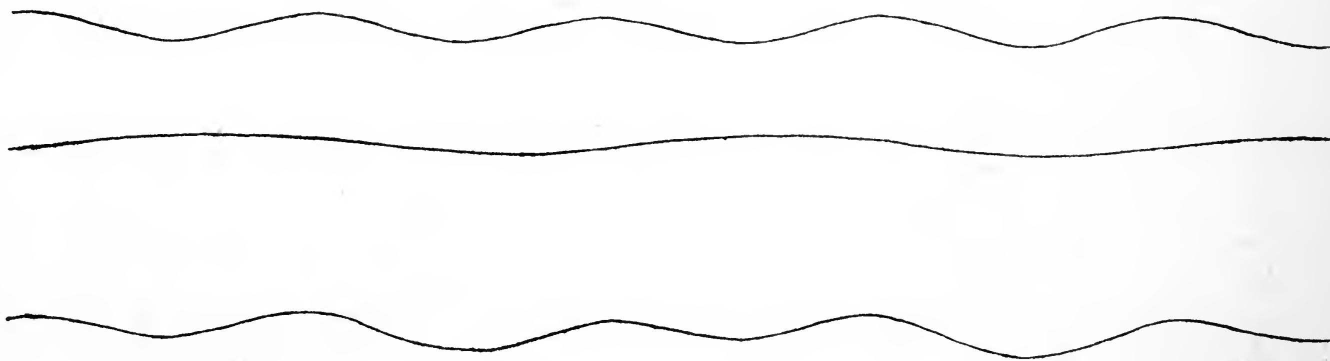
I shall now attempt to arrive at some conclusion as to the height during storms of the waves longer than those then measured, or that part of the wave-disturbance which is termed then, and afterwards, "the swell." On board ship during storms the swell is felt in the movement of the vessel more distinctly than it is seen, but it often can be perceived as a sort of broad band, lighter

[1] *Vide* J. Boussinesq, *Comptes Rendus*, cxxi.

or darker, where the whole group of shorter waves seems slightly raised, and this broad, heaved-up piece seems to travel with great speed, like the shadow of a scudding cloud.

To take the example afforded us by Sir G. G. Stokes' observation, let us think of the group of waves which he observed as they were when the wind first dropped, and think of them first apart from the shorter waves with which they were then really associated. They were not then a band 1,100 miles broad of almost perfectly harmonic undulations with length from 866 feet to 1,481 feet, but a much narrower band in which the water undulated with less regular motion, the surface having a less regular form. I shall take the average period of undulation of the water in this band as 15 seconds, and the wave-length, therefore, as 1,150 feet. This part of the total wave-disturbance I call the swell, and I inquire, What was the height of the swell? Now, the height of the principal waves shorter than the swell, *i.e.*, the dominant, or storm waves, we know fairly well from the preceding records. Most of them were 30 feet high, with fairly frequent larger individuals of 40 feet, and some of them were not much more than 20 feet high.

The diagram shows how such a condition can



COMBINATION OF WAVE 600 FEET LONG AND 30 FEET HIGH, WITH SWELL 1,150 FEET LONG AND 20 FEET HIGH. SCALE: HORIZONTAL, 1 IN. = 400 FEET; VERTICAL, 1 IN. = 200 FEET.

be represented by replacing the theoretically infinite number of wave-lengths by two, which I call the storm-wave, or the dominant wave, and the swell, the former 30 feet high and the latter 20. The lengths arbitrarily chosen are 600 feet for the former and 1,150 for the latter. It will be noticed that the combined wave in the third line represents fairly well the appearance of a tolerably regular sea, and it would do so still better if the curves had been drawn in the form of a trochoid instead of a curve of sines, which makes the trough similar to the crest.

Measuring from left to right, the vertical distance from each crest to the trough next on the right is:

	22·50 feet
	37·50 "
	18·75 "
	40·00 "
	27·50 "
Average	28·30 feet.

The average, if carried on through the whole gamut of the combined wave, would be 30—*i.e.*, the same as the height of the dominant or storm-wave. Thus, in the above example we have a range of observed wave-height from rather less than 20 feet up to 40 feet. This result, corresponding to the heights observed by me in the storm of

December 7, 1900, is due to a swell of two-thirds the height of the storm-wave and nearly double its length, the hypothetical height of the swell being 20 feet. This, however, is not an observation but a case chosen for examination.

On June 10, 1885, Abercromby, using an aneroid as already described, observed individual wave-heights of 26, 21, 23.5, and 26 feet (average 24), but obtained an absolute difference of level between lowest trough and highest crest (not, however, one of those recorded above) of 35 feet.

Let x = height of storm-waves,
„ y = height of swell,
Then $x + y = 35$ feet;

and, as we saw from the diagram referred to above—

$$x = 24 \text{ (the average apparent height)},$$

therefore—

$$y = 35 - 24 = 11 \text{ feet.}$$

This recorded case, therefore, is consistent with an amplitude of swell nearly one half as great as that of the storm-wave which dominates the eye. Had I not drawn for myself combined curves to test the effect produced by combining together undulations of a certain length with others nearly twice as long, I should not have supposed it possible to obscure a longer undulation of such considerable amplitude.

The diagrams, which I published in *Knowledge* in 1901, and afterwards in the *Geographical Journal*, May, 1904, show what is geometrically and numerically possible in the way of such obscuration. The observations made on the north coast of Ireland by Sir G. G. Stokes (as well as my own observations) show how necessary it is to allow for the presence with the storm-waves of longer waves of considerable amplitude. Abercromby's single observation supplies a confirmation of the apparently somewhat extreme case shown in the figure given on p. 98. It is, however, much to be desired that further observations similar to those of Abercromby should be obtained, for it must be confessed that it is a narrow foundation upon which to build.

On the Co-existence of Waves of Different Lengths

In studying deep-sea waves one is often called upon to decide whether to fix the attention upon the actual surface of irregular or complex form and deal with it as the concrete wave, or to think of this irregular wave as composed of, or resolved into, a number of simple harmonic waves each of regular form and of a different speed. As a matter of mathematics all irregular waves can be so resolved, and the behaviour of the roughened sea, when the wind drops, exactly performs this act of analysis—*i.e.*, of resolution into components. On account of this physical circumstance it is impossible to obtain a thoroughly satisfactory understanding of deep-sea waves as long as we restrict our mental view by the limitation of our eyesight, which generally shows us only one set of waves of somewhat irregular form running in any particular direction. Other sets of waves crossing these may be perceived by the eye, but for the present I am only concerned with those which run in one direction.[1]

The following is a generalised description of what I actually see when the wind blows upon water.

[1] A curious condition occurs when two deep-sea swells meet one another from exactly opposite directions. I observed such a case from R.M.S.P. *Atrato* on June 27, 1910. We were bound for Barbados from Southampton, and had passed a few hours before St. Michael's, in the Azores. All the way out from the English Channel we had been accompanied by a north-westerly swell. From the Azores to Barbados the sea and swell were from a south-easterly and easterly direction. On the day in question the south-easterly swell met the north-westerly, both being of only moderate height. The appearance was that, again and again, a great round-topped billow formed, which did not travel, but (a furrow appearing along its summit) quickly became double-crested, the two crests then travelling away in opposite directions.

First comes the simultaneous creation of a uniform pattern of minute waves all over the surface, then the growth of the waves to leeward, so that after a time there is a certain size of wave corresponding to the distance from the windward shore, which size is not afterwards exceeded. The growth of these larger waves at any place is accompanied by the failure and partial obliteration of the shorter waves which were there before, and this is due to the circumstance that the growth in height of the shorter waves is hampered by the vortex or eddy of the air caused by the larger series of waves. At each position there is finally a definite length of wave which is the dominant wave for that locality for the actual force of wind —*i.e.*, the class of wave which so dominates the eye that any shorter wave there appears as a mere ripple upon its surface and any longer wave is only to be detected by the presence of a sort of heaving motion which runs through the whole system of the dominant waves. On small sheets of water, or near the windward shore at sea, this swell is insignificant, but as the length of fetch of the wind increases it becomes an important part of the whole disturbance. This fact is most easily understood if we consider what happens when the wind ceases and the waves are left to themselves. Travel over a considerable distance analyses the originally complex, irregular waves into series of simple, regular waves of graduated length. The longer and swifter are in front, the shorter and slower are in the rear. But this is not all, for the shorter components flatten out very quickly as they travel, whereas the longer components preserve their height with but little diminution for long distances. Consider now the effect of this upon the surface-water at a place far distant from the windward shore. The short-length (and therefore short-period) waves will reach this place so flattened that they will produce no appreciable effect, and may, therefore, be regarded as not reaching it at all, and the water will heave with a long-period undulation, the surface exhibiting therefore only long, swift waves. Now, this gravitational travel, with its accompanying analysis of the wave-components, must go on in just the same way when the wind is blowing as it does after storms. Therefore at a considerable distance from the windward shore the state attained by the sea during a storm does not depend only upon what the wind does there, but also upon the transmission by gravity, independently of the wind, of the longer-period components of the irregular waves which the storm has created to windward. The greater the length of fetch the greater is the distance from which the surface-water draws the reinforcement of its long-period heaving, and the greater, therefore, is that part of the wave disturbance which is of greater wave-length than the dominant wave.

What, now, precisely is this dominant or storm-wave, and how is it evolved? The answer is not difficult if we think of the mode of motion of the wind as it blows over the wave-water. There must be a continual give and take between the wind and the water, such that the air above tends to go into a regular series of travelling vortices or eddies, with long-extended horizontal axes, rolling along in the hollows between the crests of a regular series of travelling water-ridges. Above this series of travelling eddies the air must flow in undulating lines, the amplitude of the undulations diminishing with the height above the water-surface, so that at a considerable altitude the air flows in straight lines. When the sea has attained to an approximately steady wave condition under the action of the wind, there is superposed upon it a train of wind-eddies (and above them, aerial undulations), which are of regularly increasing size for a long distance from the windward shore. At each successive position as we recede from the windward shore there is a characteristic, and successively larger, size of dominant or storm-wave, and this is the wave of length identical with that of the air-eddy. These air-eddies, as has been already said, hamper the development of shorter waves whose full growth would require the existence of shorter air-eddies; but they have little effect upon the longer and flatter swell, which possesses great energy, stirs the water to considerable depths, and is continually reinforced by gravitational transmission from great distances.[1] Thus it seems that in the attempt to extract precise and even numerical results for the visual observation of waves at sea, we may neglect that part of the wave disturbance which is of shorter wave-length than the dominant or storm-waves ("the waves" of common parlance), but that we must not ignore the swell, which is of greater wave-length.[2]

[1] I suspect the existence of another mechanism contributing to the same result. Referring once more to the swell running by gravity—suppose this to have attained a regular gradation of wave-length. Then each section will presumably be opaque to and absorb vibrations of its own period and transmit or be transparent to vibrations of greater period.

[2] The theory of the action of wind to increase the height of waves already running before it is that the horizontal velocity of the air being greatest at the crest, the downward pressure of the atmosphere is least there. Conversely at the trough, where horizontal velocity is least, downward pressure is greatest. Hence the trough is pushed farther down and the crest is sucked up.

CHAPTER IV

The velocity of the wind at sea—The numerical relation between velocity of wind and average height of waves—The relation between the velocity of the wind and the velocity of the waves—The connection between the rate of progress of cyclones and the character of the waves—The effect of squalls and gusts upon waves—On wave-fronts in a veering wind, and on the irregularity of the waves in the region of the Trade winds—The observed profile of waves at sea—The mountainous appearance of waves.

The Velocity of the Wind at Sea

IN order to arrive at an opinion upon the relation between the velocity of the wind and the size and speed of the waves of the sea, we have to rely mainly upon the conventional numbers entered by the navigating officer in the ship's log, by which he expresses the force of the wind as he judges it to be. The watch on the bridge being of four hours' duration, the number generally represents the average force of the wind throughout this time. The connection between these conventional numbers and the velocity of the wind has been determined by experiments with anemometers. In the case of the ordinary cup-anemometer the number of revolutions recorded during "strong breeze," "moderate gale," &c., had been compared with those obtained by whirling the instrument on a turn-table, by which means a counter air-current of known velocity is produced. The earlier experiments indicated that the number of revolutions of the standard cup-anemometer must be multiplied by three to give the velocity of the wind in statute miles per hour. More complete experiments, however, have shown that this "reduction factor" was much too high, and the factor, or multiplier, now adopted by meteorologists is 2.2. Hence the velocities of wind found in records of some years back are greatly in excess of the values now adopted. Wherever the actual logged number expressing the sailor's estimate of the force of the wind can be obtained, it is, however, easy to calculate anew the velocity of the wind in statute miles per hour, and this has been done in the present book. Thus the velocities of wind quoted by me as observed by Lieutenant Paris are not those stated by him in metres per second, but those recalculated from his logged numbers. The following table is taken from a paper [1] by Mr. R. H.

[1] *Q.J.R.M.S.*, Jan., 1897, vol. xxii., No. 101, pp. 24–55, and discussion on pp. 56–61.

Curtis on "*An Attempt to Determine the Velocity Equivalents of Wind Forces Estimated by Beaufort's Scale.*"

The third column gives what is usually called the velocity of the wind, by which is meant its average velocity. But the velocity of the wind varies very rapidly. This is particularly noticeable when the wind is strong. Every gale is gusty and affected by squalls, and columns 4 and 5 show the average range of wind velocity, corresponding to each of the numbers or degrees of the Beaufort scale.

Description.	Beaufort's Number.	Average Velocity of Wind in Statute Miles per Hour or "the Velocity" of the Wind.	Average Maximum Velocity of the Wind.	Average Minimum Velocity of the Wind.
Calm	0	2	—	0
Light air ...	1	4	5	3
Light breeze ...	2	7	9	5
Gentle breeze ...	3	10	13	7
Moderate breeze	4	14	18	10
Fresh breeze ...	5	19	25	14
Strong breeze ...	6	25	33	18
Moderate gale ...	7	31	41	22
Fresh gale ...	8	37	47	27
Strong gale ...	9	44	58	31
Whole gale ...	10	53	73	36
Storm	11	64	83	45
Hurricane ...	12	77	?	?

The Numerical Relation between Velocity of Wind and Average Height of Waves

The heights of waves discussed in detail in preceding chapters are those produced when the wind has had opportunity to develop them fully, and most attention was given to the size of the maximum waves then produced. Circumstances frequently prevent the waves from attaining the full size which the velocity of the wind is capable of producing, of which fact examples were noted in my voyage on the *Ivernia* (p. 53). The numerical relation between the velocities of wind and average height of wave, obtained from the records of daily observations on long cruises, depends in part on cases where the velocity of wind has no physical relation to the height of the waves. Such averages, therefore, blur the truths, which the writer, as a student of physical geography, desires to elucidate. There is, however, a practical point of view from which these averages may be useful—that, viz., of the naval architect. As the ships which he designs may have to sail on any seas and to encounter all weathers, it is sometimes desirable to eliminate local conditions.

The tables given in my paper in the *Geographical Journal*, May, 1904, show how closely concordant are the results from the data of Desbois, of Paris, and of Antoine, when recalculated by the modern reduction-factor of wind velocity. On an average the velocity of the wind in statute miles per hour was found to be 2.05 times the height of the wave in feet. Thus the average height of the waves in a whole gale, Beaufort's force 9, wind velocity 44 s.m.p.h., is:

$$44 \div 2{\cdot}05 = 21{\cdot}5 \text{ feet.}$$

As already explained, this average would be exceeded when the wind had full opportunity to do its work.

The Relation between the Velocity of the Wind and the Velocity of the Waves

The greatest average length of storm-waves on any one day recorded in the preceding pages is that observed by Lieutenant Paris, viz., 771 feet, which corresponds to a wave velocity of 43 statute miles per hour. The average velocity of the wind, as re-calculated from the conventional number in Paris's table, was 46 statute miles per hour. The gale had lasted (or the ship, running before the wind, had been in it) for four days, or, say, 100 hours. During the first day of the gale the wave-length was only 371 feet, corresponding to a speed of 30 statute miles per hour. Thus, during the first day the air blew over the travelling wave-crests at 16 statute miles per hour, and during the last day at 3 miles per hour.

During the storm in the Southern Indian Ocean (described on p. 73) Captain David, of the s.s. *Corinthic,* estimated the average length of the waves at about 675 feet, which corresponds to a wave velocity of 40 statute miles per hour. The wind was logged as 9 on Beaufort's scale, so that its average velocity must be taken as 44 statute miles per hour. The air, therefore, blew over the ridges of the travelling waves at an average speed of 4 statute miles per hour.

During the storm in the North Atlantic (described on p. 42) the wind was recorded by Scoresby on March 5th as a "hard gale," which I take to be the same as a "strong gale," number 9 on Beaufort's scale, corresponding to an average velocity of 44 statute miles per hour. Now, the average length of the waves measured by Scoresby on March 6th was 560 feet, corresponding to an average velocity of 38 statute miles per hour. The ship, which was running before the wind, had then been exposed to the gale for about 40 hours, but the force of the gale had by this time somewhat abated. When the gale was at its height the wind was therefore 6 s.m.p.h. swifter than the waves at their swiftest.

In the Mediterranean and other semi-enclosed seas, even where the water is deep, the length and speed of the waves are much less. Consequently the effective velocity of the wind, which maintains the eddy on the lee of the travelling ridges, is much greater.

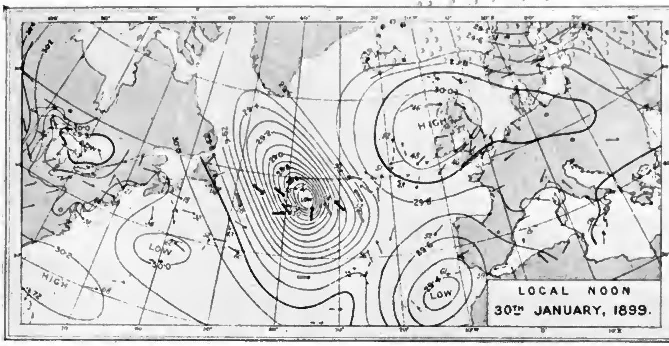
In all the above cases, which are typical, the velocity of the storm-wave is a few miles per hour less than the velocity of the wind as averaged over a period of from 4 to 100 hours.

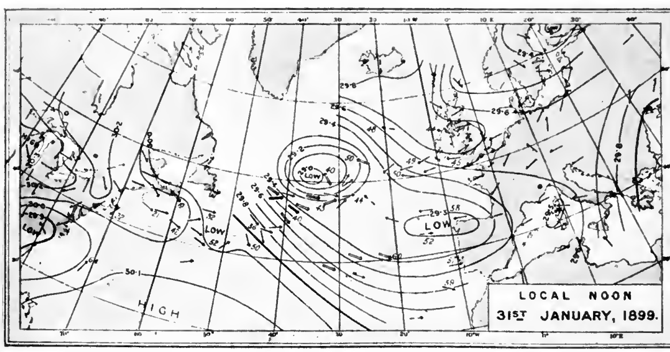
The period of the swells which break upon our shores after storms shows that they travel when in deep water at much greater speeds than do the highest waves of storms. Thus the calculated speed of the unbroken series of 139 waves which I observed at Branksome Chine on December 29, 1898, was 66.5 statute miles per hour, and that of twelve successive waves observed on February 1, 1899, was 78.5 statute miles per hour. Other observations recorded at the same locality, of which particulars have already been given, show that velocities of between 68 and 78 statute miles per hour are normal, though not frequent, for breaking swells coming to our shores from the west after storms in the Atlantic.

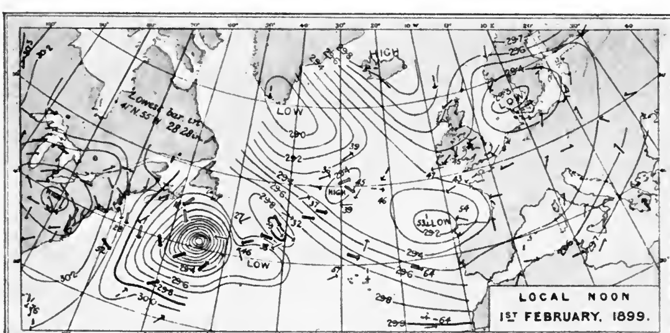
Many considerations crowd in upon the mind when we endeavour to reason upon the physical connection between the swells of this speed and the pressure of the wind during the storm. How far, for instance, can we regard the longest of these subsequent swells as having had an independent existence during the storm? For the present, at all events, I shall set aside such refinements, and simply consider the numerical speed-relation of the swiftest observed swells to the swiftest observed winds in the same part of the world, and see where this will lead us.

The storms in the North Atlantic during December, 1898, and January and February, 1899, were of such exceptional violence that the Meteorological Council made them the subject of a special inquiry, which has beene mbodied in a valuable report,[1] commenced by Lieut. C. W. Baillie, R.N., and completed by Commander Campbell Hepworth, R.N.R. The charts show that between December 25th and 29th very strong westerly winds prevailed between the Newfoundland Banks and the entrance to the English Channel. In the notes to these charts it is recorded that the velocity of the wind at Alnwick Castle, Northumberland,

[1] Charts illustrating the weather of the North Atlantic Ocean in the winter of 1898–9 (Meteorological Council, 1901).







WEATHER IN THE NORTH ATLANTIC.

(From a report of the Meteorological Council, 1901.)

attained 77 statute miles per hour at 10 p.m. on the 27th, and 71 statute miles per hour at 2 a.m. on the 28th. Beaufort's 11-12 (*i.e.*, 64-77 statute miles per hour) was recorded at sea in N. 49°, W. 35°, on 28th, and N. 52°, W. 19°, on 29th. Thus it is proved that the winds that blew had at times an average velocity 10 statute miles per hour greater than that of the swell observed at Branksome Chine on December 29th. I am not able, however, to derive the observed swell from the hurricane arrows shown on the charts for noon December 28th and 29th, for they are too far off for the swell, if travelling with the group velocity of 34 statute miles per hour, to reach Branksome Chine at the observed time. A feature of the chart for the 29th which is worth noticing is the existence of W. and SW. winds of Beaufort's 9-10 (44-53 statute miles per hour) near the entrance to the English Channel. In the moderate depths of the Channel the speed of the swell must have been so reduced [1] that the observed velocity of wind on the morning of the 29th was sufficient to exert pressure upon the swells. This may account for their reaching Branksome Chine with a height unusually great for this locality, and much greater

[1] The maximum speed of a wave in 20 fathoms is about 43 statute miles per hour.

than the height of the swells observed on February 1st.

The charts throw a clearer light upon the swell observed at Branksome Chine on February 1st. This had a period of 22.5 seconds, and therefore a speed in deep water of 78.5 statute miles per hour. A group of these swells travelling freely for a long distance under the action of gravity advances at 39.25 statute miles per hour. Now, the charts for the days January 29th to February 1st show Beaufort's 11-12 (64-77 statute miles per hour) only on January 30th, and the positions of the arrows showing force 9-10 on 31st and 1st are too distant to affect the water at Branksome Chine on 1st. The cyclonic system of January 30th half-way between North America and England is a very deep isolated depression, with wind of force 11-12 in N. 45°, W. 41°, the direction of this wind being a little S. of W. This wind, and that a little in advance of the black arrow, would send a swell almost directly to the entrance of the English Channel. The distance of the straight run from N. 45°, W. 41°, to Cape La Hogue (which I shall take as the distance to Branksome Chine) is 28°, 1,680 geographical miles, 1,960 statute miles. The difference of time between local noon January 30th in W. 41° and

3 p.m. February 1st at Branksome Chine (about W. 2°) is about 48 hours. The westerly swell at N. 45°, W. 41°, if starting at noon on January 30th, would reach Branksome Chine at the required time if it travelled at the speed of $1,960 \div 48 = 40.8$ statute miles per hour. Now the observed group-velocity of the swells recorded at Branksome Chine on February 1st was 39.25 statute miles per hour. There is, therefore, strong ground for regarding that swell as being the result of the storm which occurred two days before at a distance of nearly 2,000 statute miles.

From Mr. F. J. Brodie's paper[1] on "*The Prevalence of Gales on the Coasts of the British Isles during the Years* 1871-1900" we learn that in the great storm of December 22, 1894, the wind had a velocity of not less than 53 statute miles per hour for 14 hours (as observed, of course, at a fixed station), 64 statute miles per hour for 9 hours, and 76 statute miles per hour for 2 hours. On January 12, 1899, 53 statute miles per hour was maintained for 6 hours and 70-76 for 1 hour. The velocities attained in gusts are recorded in another paper.[2] In January, 1899, a rate of 90 statute miles per hour was recorded at Southport

[1] *Q.J.R.M.S.*, 1902.

[2] Symonds, *Met. Mag.*, May, 1900.

in one gust and between 80 and 90 in several others. The highest recorded velocity in any gust was that registered by a Dines' pressure tube anemometer at the Rousdon Observatory, South Devon, viz., 101 statute miles per hour. The results may also be expressed in this way, viz., that, at a fixed station, a wind velocity of above 70 miles per hour has been maintained for as long as 2 hours, but velocities of from 80 to 100 s.m.p.h. have only been maintained for minutes or seconds.

The greatest period of any short group of swells which I have observed is 22.5 seconds, with a speed, therefore, of 78.5 statute miles per hour. M. Bertin [1] says that 24 seconds (speed 84 statute miles per hour) is certainly beyond all observed periods in European waters. The greatest speed which I have observed in a group of many swells was 66.5 s.m.p.h. on December 29, 1898. The greatest recorded average velocities of wind in that weather were 77 and 71 s.m.p.h. on 27th and 28th of the same month.

The greatest speed which I have recorded for a group of a few swells is 78.5 s.m.p.h. on February 1, 1899. The greatest speed of wind

[1] "Experimental Study of Waves," Inst. of Naval Architects, 1873.

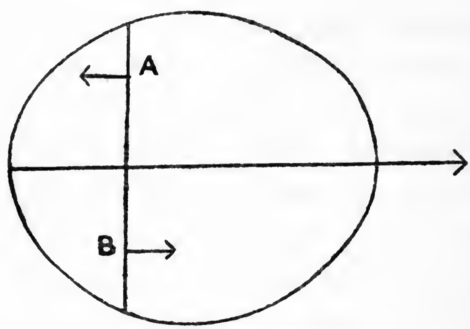
in gusts during that weather was frequently 80 s.m.p.h., ranging up to 90 s.m.p.h. in one case. This was in January.

As far as the evidence goes in this difficult part of our subject, the indication is that the maximum average velocity of wind maintained for 1 hour is a few s.m.p.h. greater than the average maximum velocity of any long group of swells originating therefrom and forming breakers upon the shores of England. It is conceivable that shorter groups of greater speed may owe their origin to gusts, but during lulls these would be running against a current of air. The maximum recorded wind velocity in gusts in 1898-99 was $11\frac{1}{2}$ m.p.h. greater than that of the swiftest of the short groups of swells.

On the Connection between the Rate of Progress of Cyclones and the Character of the Waves

Strong winds in the North Atlantic are developed in that part of an area of low atmospheric pressure where the barometric gradient is steep. These atmospheric depressions are very frequently of the form and nature known as cyclones, of which the general character is that shown in the accompanying diagram.

The oval indicates the area covered by the depression, the long arrow the direction of advance, the short arrows the direction of wind in certain parts of the cyclone. In the position marked A the direction of the wind is contrary to the direction of advance of the cyclone. Hence in this quadrant the cyclone is continually receding from the waves which its wind creates, and



A CYCLONIC SYSTEM.

along the line of advance of this part we should not expect that there would be any great development of waves, even if the winds there were strong, which they are usually not. Obviously, for a given velocity of wind, the position most favourable to the development of waves is that where the direction of the wind coincides with the direction of advance of the cyclone. This is where the direction of the wind is shown by the arrow B. Here, moreover, at about 4-10ths the distance from centre to edge, the strongest winds are usually developed. The line of advance of B will, therefore, be the line along which the greatest wave-development will occur. There is not any constant relation between the rate of advance of a cyclone and the velocity of the winds locally developed within its area. Considering only the critical position B in the cyclone, the rate of advance of the cyclone is, from our present point of view, simply the rate of advance of the locus of the force which is there creating the waves; we have to do, in fact, with waves created by a travelling disturbance. Let us consider groups of simple harmonic waves of different lengths, and therefore different speeds, to be already formed and to be travelling together (and therefore superimposed upon one another) as forced waves pressed upon by the wind. This wind, however, in a progressive cyclone is a "travelling disturbance," and while it will, to some extent, increase all the waves beneath it which it can press upon at all, the waves which move slower than the travelling disturbance are being left behind all the time. On the other hand, all waves whose velocity is greater than that of the travelling disturbance run ahead of it, and are no longer subject to the reinforcing action of the wind. The waves whose speed is identical with that of the travelling disturbance will be continually subject to the reinforcing action of the wind during the whole lifetime of the cyclone. I think, therefore, that the wave-length of the principal, or dominant, or storm-wave generated in Atlantic storms should depend, not only upon the velocity of the wind, but also upon the rate of advance of the cyclone. It is, I believe, a matter of common remark that in some storms a short, steep sea is soon formed and in others a longer sea.

The general rate of advance of Atlantic storms towards our shores has been investigated,[1] and the figures are worth examining in connection with our subject. Storms advancing from points between WSW. and WNW. to ENE. and ESE. travel at an average speed of 28.9 statute miles per hour. Of the 264 storms examined, only 60 travelled at more than 35 statute miles per hour, and of these only 10 travelled at more than 52½ statute miles per hour.

It appears, therefore, taking the average of a large number of storms coming from the Atlantic, that waves travelling about 30 statute miles per

[1] *Q.J.R.M.S.*, 1902, *loc. cit.*

hour [1] (length 371 feet) should enjoy special opportunities for development in depressions where the wind exceeds that velocity.

We see, therefore, that waves of 68-78 statute miles per hour, which are the greatest speeds I have recorded for swells after Atlantic storms, would in almost all cases outrun them, even when the depression advances along a straight path. The reason that such waves are not developed to greater heights is, therefore, not only that the wind is, during most of the time, not strong enough, but also that the cyclones advance too slowly.

The above method of theoretical treatment is of only occasional application on account of the fact that there are generally several neighbouring cyclonic systems on the North Atlantic and that the actual winds are a compromise between them. Fortunately, the charts for December 27, 28, and 29, 1898, enable us to examine an instance of this commoner condition. A series of cyclonic systems were following one another across the North Atlantic from S. of W. to N. of E., and strong westerly winds prevailed during the whole of these three days between N. 50°, W. 40°, and

[1] This is a wave of a little more than 8 seconds period. The 8-seconds wave has a speed of about 28 statute miles per hour and a length of 328 feet.

the entrance to the English Channel. The unusual force of Beaufort's 11-12 was at local noon on December 28th recorded in the neighbourhood of N. 50°, W. 37°, and not elsewhere, and on local noon December 29th in the neighbourhood of N. 49°, W. 19°, and not elsewhere. As the storm does not appear to have abated meanwhile, we may infer that the locus of the hurricane wind progressed continuously along this path of 840 statute miles in the course of these 23 hours. This is at the rate of 36.5 statute miles per hour. The average wind velocity for 11-12 is 70.5 statute miles per hour. Waves travelling at nearly this speed would be running on ahead all the time. The waves which would be all the time from noon December 28th to December 29th subject to the maximum force of wind would be those with a speed of 36.5 statute miles per hour, and, therefore, with a length of about 558 feet. As they would be subject to an effective wind velocity of $70.5 - 36.5 = 34$ statute miles per hour, there would be a great deal of spraying from their crests.

Two hours at a fixed station is the greatest time recorded above for wind with an average velocity of more than 70 statute miles per hour. If the locus of that wind force were advancing at 36.5

statute miles per hour, as in the above case, the length of fetch, or stretch of water, at any one time subject to this wind would be 73 statute miles, in which there would be a train of only 200 of the 1,918 foot-waves.

It may in this connection be noted that in a gust lasting 1 minute, and in which the locus of application is advancing at the same rate (36.5 statute miles per hour), the length of fetch would be only about half a mile—*i.e.*, less than two of the above wave-lengths. The absence of breakers with speeds nearly as great as the maximum wind speed of gusts may, therefore, be properly attributed as much to their insufficient length of fetch as to insufficient time of action.

The charts for February 2 and 3, 1899, in the publication of the Meteorological Council to which I have so often referred, afford an excellent example of a long-continued hurricane-force of wind which was stationary in position for 24 hours. After examining these two maps, I made the following note, viz:

"Maps for February 2nd and 3rd show hurricane-force (centre about N. 45°, W. 45°), with no appreciable length of fetch indicated, occupying almost the same considerable frontage for 24 hours. In this area must have been a very wild sea with the waves spraying very much, from which must have emerged a very long swell."

After making this memorandum I referred to the notes on page 6 of the publication, and found:

"On February 2nd . . . the *Quernmore*, in N. 41°, W. 46°, reported that during the storm the atmosphere was so heavily charged with spoondrift as to appear as a heavy snowstorm."

My reason for diagnosing an exceptional amount of spraying was that the locus of the hurricane-force did not advance, so that the wind would not have been able to develop the longer waves.

The Effect of Squalls and Gusts upon Waves

On December 22, 1906, I was on board the Leyland S.S. *Jamaican*, bound for Puerto Colombia from Liverpool, in N. Lat. 38° 21′, W. Long. 35° 43. There was a heavy sea and a moderate gale. At 4 p.m. a violent squall of wind, with rain, occurred, lasting about 4 minutes, which was accompanied by very big waves, and succeeded by comparatively calm water. I guessed the largest waves during the squall to be 7 feet higher than those which preceded or followed.

On the following day, December 23rd, we were in N. Lat. 35° 47½′, W. Long. 39° 48′, with a strong breeze verging on a moderate gale—*i.e.*, a wind velocity of about 28 statute miles per hour. At 3 p.m. there occurred a squall lasting 3 minutes, which converted a moderate to a large sea. I estimated that the height of the waves increased at least 2 feet per minute, finally attaining rather more than 20 feet. Not only did the waves increase in height, but the crests lengthened out transversely, so that the waves ran in longer and more regular ridges. The squall came from the starboard and abaft. Two minutes after it had passed us we were among waves no larger than before, but I could see a group of about four great ridges travelling away with the squall. The length of the waves, as judged by their appearance in relation to the ship's length, was never more than 200 feet. As has been already explained, this estimate is generally less than the measurements obtained by following the waves in their course.

In another squall, occurring at 5.2 p.m. and lasting 5 minutes, the height of the waves was perceptibly increased.

Next day, December 24th, we were in N. Lat. 33° 38′, W. Long. 43° 58′. The principal " waves " were mounds of water, produced by the crossing of two sets of waves. At 3.30 p.m.

the wind began to fall, and at 4 p.m. the sea was slight, except for the occasional formation of a larger mound of water. At 4.55 p.m. a black being very dense and apparently rainy. The part. head. It reached from the horizon on one side of us to the horizon on the other side, the two ends being very dense and apparently rainy. The part of the cloud directly overhead was thin, and discharged only a few small drops of rain. The passage overhead of this central part was accompanied by only a slight additional breath of wind, but with it came a big swell, comprising 12 or more large waves, and the ship, previously steady, began to roll heavily. In 5 minutes the cloud had passed, and in another 10 minutes the sea had quite returned to its former state.

These observations relate to squalls occurring towards the end of stormy weather, coming upon a fairly large swell running in the same general direction as the wind. They show that (according to my guesses of height) a sudden increase of wind can restore the height of waves at the rate of 1 or 2 feet per minute. They illustrate the fact that, when the system of travelling ridges is already formed, the wind, falling into eddies between them, has greater power to raise the crests and depress the troughs, a power of swift and immediate action which contrasts strongly with the slight power of the wind when blowing upon smooth water. My observations from the S.S. *Jamaican* relate, as I have said, to the action of squalls at the tail end of a storm.

Their action during the height of a storm is often to lower the waves. Thus, during my voyage from Liverpool to Boston on the Cunard S.S. *Ivernia*, December, 1900, of which some particulars have already been given, I often saw the effect (which others have frequently described) of showers of spray from every wave-crest during each gust. The steepness and the slowness of the waves were such that the cohesion of the water at the crests could not resist any increase of the upward suction and the horizontal pressure there. Hence in the gusts the water was torn in showers of spray from the crests, falling finally, one must presume, mainly in the sheltered troughs, thus tending to flatten out the sea.

On March 11, 1901, on the Red Star S.S. *Vaterland*, east-bound from New York to Southampton, I saw the much greater lowering effect of a wind meeting the waves. We were in N. Lat. 44° 56′, W. Long. 36° 54′, with a rough sea from the starboard, the waves occasionally rising above the horizon of our promenade deck. At about 4 p.m.

the wind quite suddenly chopped round and blew from the opposite direction, meeting the waves in their advance. The ridges of the waves, as usual, were not uniform, but had, on the contrary, an undulating outline. The wind caught the higher portions, and bit huge pieces out of them which momentarily formed a milk-white cloud, which in its turn was quickly dissipated in spray.

On Wave-fronts in a Veering Wind, and on the Irregularity of the Waves in the Region of the Trade Winds

Wind is never really steady. Not only is it always more or less gusty, but it is always veering—*i.e.*, changing its direction. Apart altogether from the progressive variation in the general direction of the wind which is characteristic of a cyclonic system, there is a rapid veering about a mean position, even in the Trades. The amount of this veering is sufficient to exercise an important effect upon the character of the waves and the appearance they present.

It results in the formation of waves running simultaneously in slightly different directions, and thus, even in the regions of the Trade winds, the open sea does not present a series of parallel ridges, each one of uniform height, with a lateral extension many times greater than the distance from crest to crest.

In 1907 I made the following observations on the want of regularity of waves created by the Trade winds. On January 8th, *en route* from Colon to Kingston, Jamaica, in a strong NE. Trade wind, I estimated the height of the principal waves at 15 feet. Their apparent length was about 200 feet. I noted at the time that this strong breeze had continued, to my knowledge, for eight days, and that for some days past there had been no increase either in the size of the waves or in their regularity, indicating, therefore, not only that the maximum size is soon attained (as M. Bertin [1] has pointed out), but also that there is no continuous approximation towards regularity. The captain of the vessel (S.S. *Jamaican*) stated that on such a day as this the wind would not vary more than one point of the compass in the course of a four-hour watch, and this is reckoned a very steady wind. But one point of the compass is $11\frac{1}{4}$ degrees of arc, which is a very appreciable angle. If one watches the arrow of a sensitive weathercock in a strong breeze, in our own country, it will be seen

[1] Memoir on the "Experimental Study of Waves," Inst. of Naval Architects, 1873.

that it never remains stationary for more than one or two seconds, but is continually shifting through a large angle.

Another cause can also be divined for the unlevel tops of the wave-ridges and their small lateral extension. This cause is a greater force of wind to right or left of the ship's course. Suppose, in the first place, that the ship is in a calm, and that to the starboard and in front there is a head wind blowing. Then a swell will spread out laterally from that area, meeting the ship obliquely on the starboard quarter. Secondly, if a lighter head wind be blowing where the ship is, the wind-waves will be crossed obliquely by this swell from the starboard, even though the wind there be blowing in the same direction as that where the ship is. The velocity of the wind being less where the ship is, it will not be able to regularise the obliquely-running, swifter swell.

The wind-formed waves which run in the most regular ridges (*i.e.*, of the greatest lateral extension as compared to their wave length) are of two orders of magnitude. First, the small waves of a few feet in length and not more than one foot high; second, the large ocean waves. The regularity of the first is not affected by long-period veering of the wind, for they die out completely in the interval and fresh sets are formed. The regularity of the second is not visibly affected by short-period veering, being too massive. Waves of intermediate size are affected by both kinds of veering and several crossing sets are formed.

The Observed Profile of Waves at Sea

Both during a wind and in the case of a swell travelling calmly in deep water, the trochoid represents the apparent form of the wave much more nearly than the curve of sines, for it is easy to observe that the convex part of the wave has a steeper curve than the concave part, the crest being narrower than the trough. But, except in the case of a somewhat flat swell, the greater steepness of the front face of the wave is obvious to the eye, and most markedly so when the wind is blowing. Now, Sir G. G. Stokes found [1] that waves of permanent type in deep water, whatever be the order of approximation to which the calculation is pushed, must be symmetrical with respect to vertical planes passing through their ridges. I conclude, therefore, that steep waves at sea are never waves of permanent type. Again,

[1] "Math. and Phys. Papers," vol. i., p. 193, from *Trans. Camb. Phil. Soc.*, vol. viii., p. 441.

both Stokes and von Helmholtz showed that for a single series of waves of permanent type the condition under which greatest steepness could be attained was that the speed of wind and wave should be equal.

Now, according to observation, the steepest wind-waves in deep water are formed where the speed remains small relatively to that of the wind—*e.g.*, in lakes and small seas. Also in the Trades, where the wind is perpetual, there is no sign or symptom of an approach to the " highest wave " of Helmholtz and Stokes. I conclude, therefore, that observation indicates that under natural conditions of wind there is no tendency to progressive approximation towards the state of one set of waves of permanent type.

In this connection, I note that Professor Horace Lamb, who has investigated water-waves as a mathematician, writes [1] that " the possible form of waves of permanent type . . . is very interesting mathematically . . . but no reason has been given, so far as I know, why free water-waves should tend to assume a form consistent with permanence."

[1] Presidential Address, Section A, British Association, Cambridge Meeting, 1904.

On the Mountainous Appearance of Waves

The phrase " waves mountains high " has long given offence to literary landsmen, who quote measurements to show that waves are not even as high as hills. I have never met a seaman who either supposed or pretended that waves were as high as mountains, but there are conditions when waves look like mountains, or, at any rate, like large hills.

This happens when the majority of the crests rise well above the line of sight, especially if the atmosphere be rather thick, so that minute detail is obliterated. Four or five ridges, with the intervening three or four troughs, then fill all the space between the eye and the horizon. Being mounted on a deck, there is a feeling or impression that the horizon is at the distance which it would have on land with such an eye-elevation. This would mean a mile or more from ridge to ridge, which is ten times the actual distance ; and the apparent height is consequently increased in the same ratio, making a wave of 40 feet look as high as a hill of 400.

I have seen, and recorded,[1] a case where absence

[1] *Geographical Journal*, Jan., 1900, "On Desert Sand-dunes Bordering the Nile Delta."

of surface detail produced a somewhat similar illusion of great size among desert sand-dunes. Particularly when under a low sun they produced as great an impression of size as mountains thousands of feet high—*i.e.*, of ten times their real height.

NOTE TO PAGE 60.

In storms of exceptional duration as well as of more than ordinary severity, such as are not encountered every year, the waves are somewhat higher. Thus in February, 1910, the R.M.S.P. *Oruba*, between Southampton and Barbados, encountered waves which, from the account given me by Captain C. P. Langmaid, appear to have attained 45 feet. In March, 1904, Captain J. G. K. Cheret, on another of the R.M.S.P. steamers, encountered between Southampton and the Azores exceptional weather, of which he has given me an account. When he was on the bridge the waves frequently obscured the horizon at times when the ship was on an even keel, from which it appears that they surpassed 45 and may have attained 50 feet.

PART II

ON THE ACTION OF SEA WAVES TO TRANSPORT SHINGLE, SAND, AND MUD

CHAPTER V

On the depth to which wave-agitation extends, and on the transport of fine mud—The action of waves to drive shingle shorewards—The effect of percolation to promote the building-up of beaches—The movement of sand by waves—The undertow.

On the Depth to which Wave Agitation Extends, and on the Transport of Fine Mud

WHEN the surface of the deep sea is in waves, the agitation extends to some depth. For our notion of what goes on below the surface we have to depend mainly upon theory, observations being almost wholly wanting. According to theory, if there be one set of regular trochoidal waves running, the repeated motion of any particle of surface-water is a vertical circle.

In the upper half of the circle the motion of the particle is forwards—*i.e.*, in the direction of advance of the wave. In the lower half it is backwards. Thus the return flow of the wave-water in a travelling wave is not a precise reversal of the onward flow, for it takes place at a lower level.

Below the surface trochoid are sub-surface trochoids, in which the diameter of the circle which the particles of water describe diminishes with increasing depth.

The diameter of the circle and the velocity of the oscillating currents diminish in geometrical progression as the depth increases in arithmetical progression, the diameters being halved for an additional depth of 1-9th wave-length below the mid-level of the surface wave. Thus, at a depth equal to one wave-length, the diameter of the circle, and the velocity of the moving particle of water, is 1-512th of that at the surface. Thus, in the case of a wave with a length of 600 feet and a height from trough to crest at the sea's surface of 40 feet, the particles of water at a depth of 600 feet will revolve in a circle of 40 feet ÷ 512 = 0.94 inch diameter. The period of a 600-foot wave is about 11 seconds, and this is the time in which the particle at a depth of 600 feet would describe a circle of about 1 inch diameter.

We have seen that waves of the greatest height are seldom more than 600 feet long in the North Atlantic, and it is seldom that very long swells, being much lower, would give a greater agitation

THE PROFILE OF BREAKING WAVES AT EASTBOURNE.

than this at a depth of 600 feet. The line of 600 feet, or 100 fathoms, is a very important depth in the seas, for it is approximately that to which the edges of the continents are submerged. From this line the sea bottom descends abruptly to the vast depths of the great plains where the soundings are reckoned in thousands of fathoms.

At such depths the agitation caused by wind-waves must be absolutely insensible, but within depths of 100 fathoms, *i.e.*, on the continental platform, continual slight oscillations of 10-20 seconds period, and even as little as 1-inch amplitude, must exert an effect in hindering the deposition of the finest kinds of mud. Mud, or dust, when so finely divided that it settles through air or through water with indefinite slowness, only comes to rest where the fluid is free from agitation, unless some agency —*e.g.*, chemical or electrical—precipitates the particles. Every student has noticed that it is not the exposed papers which he is handling frequently on his desk which become dusty, but those put away—*e.g.*, on the top of a high bookshelf.

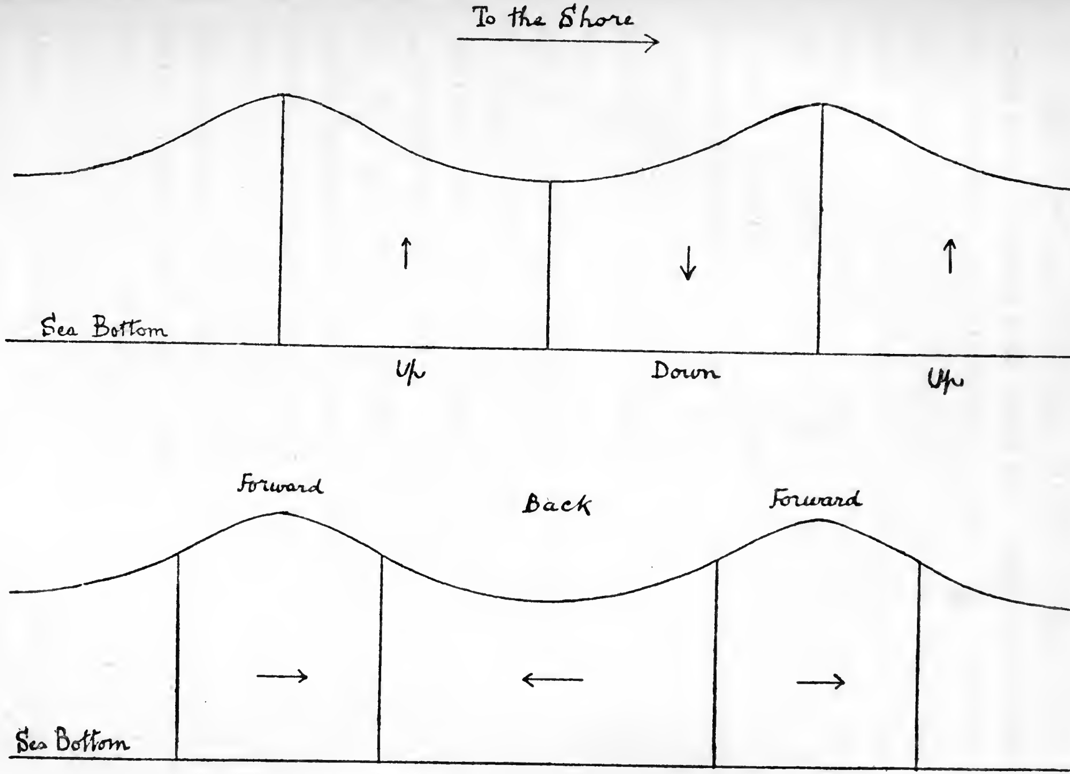
We may say with confidence, as a theoretical inference, that the agitation of wind-formed waves affects the bottom of the sea as far as the edge of the continental platform to such an extent as (in co-operation with tidal and other currents) to keep very fine mud moving about until it has an opportunity of subsiding over the edge of the continental shelf—in the absence, that is to say, of chemical or other coagulation of the fine particles into clots or lumps.

The Action of Waves to Drive Shingle Shorewards

It is matter of common experience that the stones brought on to the sea-shore (*e.g.*, by the wasting of gravel cliffs or by the wash of stone-carrying torrents), though swept along the coast and thus distributed, are to a great extent rejected by the sea and piled up in a bank, so that some of the stones are only reached again by the largest waves at the times of high water of the greatest tides. Classifying the detritus brought to the sea-shore into three sorts, viz., shingle, sand, and mud, we may say that those parts of the sea bottom which are subject to wave disturbance afford no abiding place for either the first or the last.

We have seen how the mud travels on the whole in a direction contrary to that of the swell, which, having "felt the bottom," is advancing shorewards.

I now put forward a theory which I think shows that the oscillations of the bottom water where agitated by progressive waves has a proper action of its own to heave forward—*i.e.*, in the direction



VERTICAL AND HORIZONTAL CURRENTS OF WAVES.

of the waves' motion—all detritus which they can wholly or partly lift from the bottom, but cannot maintain more than momentarily in suspension. I will first suppose the waves to be symmetrical, which is the condition least favourable to proving my case, and I will begin by supposing the bottom to be horizontal. The vertical currents are as shown in the first figure; *i.e.*, an upward current begins when the trough passes and continues until the arrival of the crest, after which subsidence commences and continues until the next trough arrives.

The horizontal currents are as shown in the second figure. The shoreward current begins in the midst of the upward current. The material which has been raised by the upward current is caught thereby and heaved shoreward, and the shoreward current, acting after the commencement of the down current, continues to drive the material forward during the first part of its period of subsidence. The backward horizontal current then sets in when the water has been clarified from all coarser and rapidly subsiding materials, so that at its commencement it only finds fine material in suspension, which it carries backwards. During the last part of its period of action the backward horizontal current is accompanied by an upward

WAVES BREAKING ON A SHINGLE BEACH.

current, and coarser material begins to be carried backwards; but this backward movement is more than neutralised by the succeeding forward current, which has the advantage of acting upon material already suspended, or, in the case of large stones, already loosened from their anchorage.

Next, let us consider the case of waves approaching the breaking condition; and here I can rely upon personal observation, particularly upon the moderately flat, sandy shore between Bournemouth Pier and Branksome Chine, Dorset. When the wave is in this stage the front is much steeper than the back, the upward current (trough to crest) is short-lasting, but very violent. The reversal of horizontal current sets in very suddenly, the shoreward current attaining its maximum speed very quickly, while the water is heavily charged with the coarser sediment. The change from shoreward to seaward current and from upward to downward current is, on the other hand, very gradual. At its commencement the seaward current is also very gentle, and it only attains great intensity just in time to have its effects upon the coarser sediments reversed by the sudden onset of the shore current which accompanies the advancing wave-crest.

When the wave actually breaks upon a bare shore there are two additions to its mode of shoreward action upon pebbles. In the first place, and obviously, the cataract which is discharged obliquely upon the ground drives pebbles forwards. In the second place, if we look at what happens just behind the fallen front, we see that, instead of subsidence and backward flow, there occur upwelling and shoreward flow. The reason is evidently that the head of water in front has been destroyed, the pressure is now from behind, and the breaking wave has, in fact, rolled over.

It is evident that this predominantly forward, or shoreward, action of nearly, and quite, breaking waves upon pebbles could be neutralised by setting the waves to roll the pebbles up a slope. There would be a slope of some particular steepness on which gravity would just neutralise the forward action of the waves.[1]

Moreover, since the advantage of the forward action over the backward action so much depends upon quick subsidence of the particles, it appears a proper inference that upon a moderate seaward slope there will be a travel of large material shoreward, while material of a somewhat smaller size will merely oscillate.

[1] This is a reason against the construction of steep groynes.

A WAVE BEFORE AND AFTER BREAKING.

The Effect of Percolation to Promote the Building of Beaches

When I have watched the action of the breakers upon a natural sloping platform of hard rock, cut at the foot of a cliff, it has seemed to me that the stones thrown forward by the breaker roll down so freely in the backwash that a moderate slope is sufficient to return to the breaker as many stones as it rejects.

It is otherwise, however, when the shore is already covered with a sloping bank of shingle. The wash from the breaker, rushing up this bank in virtue of the speed with which it starts, travels over its surface, filling only the interstices between the upper layers of stones, and leaving the interstices of the greater part of the bank above the mean sea level unsaturated and void. When the wash of the breaker has reached its limit and the water begins to run downhill, a great part of it subsides through the interstices of the shingle instead of flowing as a surface-current, so that the latter is weakened in two ways. There is the diminution of momentum which lessens its power to roll stones down, and secondly there is the diminution of depth which results in the larger of these stones being only partly submerged. They are thus often stranded through loss of buoyancy. This stranding effect is seen best, however, in the wood, seaweed, corks, &c., which are left in a marginal fringe at the furthest reach of the wash from the waves.

The proper effect of waves, when acting without complicating circumstances, upon a sufficient supply of shingle is to construct a bank or ridge upon the top of the beach, the face of which is of very steep and uniform slope. These banks are called Fulls, and are a characteristic feature where-ever shingle beaches extend seawards upon our shores—*e.g.*, at Dungeness.

The Movement of Sand by Waves

Sand neither remains suspended indefinitely, as mud, nor drops instantaneously, as shingle, but settles through water at a moderate rate, which for the beach sand at Branksome Chine, Dorset, is about 2 inches per second. Unlike fine mud, which the wave-water of the sea passes on to the great depths; unlike the shingle, which the waves reject upon the shore; the movement of the sand is very variable, changing more than that of the mud or shingle with the varying agitation of the sea. My own observations on seashore sand have been made on the coasts of England, Scotland, and Wales, but

WAVE BURSTING AGAINST A VERTICAL WALL.

chiefly in the English Channel, and almost daily during some years on the beach near Branksome Chine, between Bournemouth and Poole Haven. They do not apply to lakes or tideless seas.

Usually the floor of our seas is covered with clean sand, from the lower parts of the beach which are uncovered daily by the recession of the tide, to depths as great as enable the bottom to be seen from a boat. In greater depths the sand dredged up is less clean and homogeneous. In addition to this covering of sand upon the floor of the shallow sea there are here and there great banks of sand rising nearly to the surface from water of some depth. Such are the Skerries Bank, east of Start Point (Devon) and the Shambles Shoal, east of Portland Bill (Dorset). Also, where shingle is not too abundant, the whole of the surface of the beach is often composed of sand (which buries the occasional stones). In such localities one may often see the breakers piling up a ridge of sand on the top of the beach in the manner already described for the shingle Fulls. The water does not, however, drain out of the sand-ridge so completely between waves, and the influence of percolation upon accumulation is, therefore, not so great as in the case of shingle, although it is still a main factor in the accumulation of the ridge at the summit of the beach.

From time to time, and generally after storms of exceptional severity or long duration, or accompanied by high tides, the clean sand is wholly removed between the levels of high and low tide, and much is also removed at even lower levels. We then see during low tide the eroded rock which is the real floor of the foreshore. At high tide the sea, even if calm, then reaches its bounding cliffs, and we realise that the sandy covering of the foreshore, though generally there, is not a permanent deposit, but only a covering which is stripped off when the forces of the sea are really set to work.

After the beach has been stripped by storms near Branksome Chine the slope of the shore has been much reduced, and in the calm weather succeeding, especially with an off-shore wind, I have often watched the sand being brought back and piled up by the breakers in a sand Full, or ridge, often with a lagoon behind it at high tide. The waves have then the shoreward action on the sand which has already been described in the case of shingle, the settlement of the sand being, I presume, sufficiently rapid in the case of these small waves in the presence of little other agitation—as, *e.g.*, of tidal or other currents. When the wind is off-shore there is probably a slight shoreward undertow assisting, as to which I shall have more to say. Apart from this,

BREAKER AND BORES ON A FLAT SHORE.

however, the mere action of a small swell from the offing appears to bring the sand in here when the slope of the shore has been reduced almost to nothing. The shoreward action does not then cease with the breaker; for the waves, breaking far out, produce another kind of wave, the bore, a wave of permanent form with a precipitous foaming front. There is always a procession of these in advance of the breaker-line, and they thin themselves from less and less to nothing as they advance to the shore. Sand-ripples over which they pass (when not wholly obliterated) are no longer symmetrical, but face shorewards, and, presumably, travel shorewards. The action of these waves upon quickly subsiding material is predominantly shorewards, being an exaggeration of that already described for waves about to break.

After a time of fair weather, a moderately sloping foreshore and a beach of clean sand is once more formed here, and equilibrium is re-established for such weather, the slope being a measure of the excess of shoreward over seaward action proper to the waves.

All this process which I have described differs, however, but little from that already specified for shingle, and the reader will naturally be more inquisitive as to the explanation of the reversal of this in prolonged rough weather.

An important part of the explanation is in the seaward currents generated during such weather, with which I shall have to deal presently, and for the moment I will only specify that part of the mechanism of removal which is due to the waves considered as merely oscillating—*i.e.*, without any resultant current. When the sea is very rough the agitation of the bottom-water is so violent that the sand cannot settle. It must be remembered that wherever there is a swirl of water with an upward velocity of even as little as 2 inches per second the sand cannot sink. Thus, as may be readily perceived by the eye, the rough water becomes turbid with the sand, as if the sand were so much mud, and the mechanism of shoreward transport of quickly subsiding particles no longer applies. The sand behaves, in fact, more like mud or dust, and (even if there were no seaward undertow or other seaward currents) it would tend to shift to deeper water where the bottom agitation is not too great to allow it to settle.

On the Undertow

At Branksome Chine there is a typical sandy shore of moderate slope, which is not exposed to strong tidal currents. The exposure is southerly, and there is a headland a few miles to the westward.

THE FRINGE OF FOAM LEFT BY THE BORE UPON A FLAT SHORE.

Thus in an ordinary cyclonic storm, advancing from the Atlantic, the principal waves, rounding Old Harry Rocks to the westward, come in directly upon the shore with a south-westerly wind more or less behind them. In the clearing weather which generally follows, with north-westerly wind, the waves generated at a distance continue to advance upon the shore, but the wind is now against them, and spray is often torn from the crest of the breaker and driven seawards. Under these different conditions the position of the breakers is quite different. In the first case—*i.e.*, with strong on-shore wind—there is more than one line of breakers, but even the final line is situated far from the shore, and between it and the beach there is a somewhat numerous series of bores, or roll waves.

When, on the other hand, the wind is off-shore, with a rough sea in the offing, waves do not break until they come quite close to the beach. The breakers, moreover, curl over in a well-formed cusp and occasion a loud report. This noise is apparently due to the escape of the air which has been momentarily imprisoned when the cusp has curled over upon the front of the wave. Although they come so close to the shore before breaking, their height, reckoned above the antecedent trough, is sometimes as great as that of the breaking waves during the previous on-shore wind. I found that when the water was but little above my knees the crest of the wave about to break close by was considerably above my head, showing that the wave remained unbroken when the depth of water immediately in front was considerably less than the height of the wave from trough to crest. In a rough sea with on-shore wind the cusped breaking waves were formed much beyond the limit of a man's depth. These waves not only broke farther out, but also when the cusp was not perfectly formed. The upper part of the crest folded itself down upon the front face, becoming a mass of seething water, and the wave then travelled on as a bore with its head of froth. The motion in the frothing head was violently shorewards, and it was impossible to swim in it.

Many measurements have been made by engineers to determine the depth of water in which waves break. Very roughly the general result may be expressed by saying that the depth of water (reckoned from the undisturbed sea-level) is equal to the height of the crest above the trough. I shall not pause to discuss the somewhat unsatisfactory mode of expression, the point I wish to bring out being that the more those measurements have multiplied the clearer it has become that the ratio is not even approximately constant. It is quite different, not only for shores of different slopes, but also for a given shore it is quite different during on-shore and off-shore wind respectively. Thus Colonel D. D. Gaillard, U.S.A., found [1] that with a given locality and a given slope a wave broke in a depth of water equal to $1\frac{1}{4}$ times its height when there was a strong wind blowing shorewards, while with an equally strong wind blowing off-shore the wave remained unbroken until the depth of the water was only $\frac{3}{4}$ of its height.

When there was no wind and the breakers were due solely to the ocean swell the wave broke in a depth of water equal to the height of the crest above the trough when the slope was 1 in 100, but when the slope was 1 in 12 the wave broke when the depth was more than twice the wave height.

The breaking of a wave is, of course, due to the water near the surface in the crest of the wave moving much more quickly forward than the water immediately below it. This condition must be reached sooner or later when ordinary waves from the deep sea advance in the continually shallowing water caused by a sloping bottom. On the

[1] "Wave Action in Relation to Engineering Structures," Washington, 1904, Chapter VII.

steeply sloping shore of a shingle beach at the highest level of the tide we can at any time see that strong rushes of water are poured back in a shallow sheet to the foot of the breakers. It is not difficult to understand that the effect on the bottom water just beyond the breaker of this strong intermittent current will be to diminish the velocity of the bottom current under the crests and increase the seaward velocity of the current under the troughs.

The more the shoreward bottom current is checked under the crests, the deeper will be the water in which the wave will break.

It is well established that wind at sea causes a current which is strong at the surface, but of which the intensity decreases rapidly with depth. Thus, quite apart from any slight translation of water which may be theoretically deduced for trochoidal waves, there is a surface drift in a storm at sea which has the following effect upon the oscillations of a particle of water at the surface, viz., at the end of each complete oscillation it has advanced in the direction of the wave when the wave is running before the wind. Thus, in an on-shore gale there is a surface drift, which takes place in jerks, towards the shore, and this goes on as long as the gale endures. But the level of the

WAVES APPROACHING ONE ANOTHER IN VERY SHALLOW WATER.

water does not rise proportionately to the amount driven shoreward, for a head of water accumulates which in time prevents a further rise. The surface drift, indeed, continues, but the undertow is increased, so that the amount of water receding from the shore is equal to that approaching it. In the case of a prolonged storm when the wind blows into a bay and there is a steep beach, it seems quite possible that the undertow may be so strong that the bottom current is continuously seaward, although it would, no doubt, be jerky, the seaward motion being checked as each wave-crest passes. These are the conditions under which even shingle may travel seawards from the foot of the breaker.

If, however, there be no terminating cliff or sea-wall, so much of the shingle as is only reached by the extreme wash of the water discharged from the breaker will, I think, still be driven shoreward, owing to the effect of percolation.

That off-shore wind produces up-welling of water against a coast-line has been proved on the large scale by observations of temperature and salinity, and it follows that there must then be a sort of shoreward undertow. Its intensity must be much less than that of seaward undertow during on-shore winds, but it doubtless increases the normal shoreward action of the waves.

CHAPTER VI

On the actions which determine the 'longshore transport of beach shingle—On the causes which give rise to an arrangement of pebbles according to their sizes along the Chesil Beach and certain other beaches—On the production and maintenance of the Shambles sand-bank near Portland—The formation of patches of shingle upon a sandy beach by the action of breakers.

On the Actions which Determine the 'Longshore Transport of Beach Shingle

When the sea is smooth, the shingle of our beaches lies undisturbed by the tidal currents. The 'longshore drift of beach shingle is therefore ultimately due to the wash of the breakers, and in order to judge of the effect of the tidal currents upon 'longshore drift, we have to consider how the motion of this wash-water is affected by them. Where the shingle beach is on a straight line of coast where the tidal current runs strongly past the shore while a fairly heavy surf is breaking, the appearances presented to the spectator on the shore are deceptive. The breakers discharging at right angles to the shore are noisy and conspicuous; the

WAVES SHOWN BY DISTORTED REFLECTION OF MASTS (KINGSTON, JAMAICA).

steady current parallel to the shore is silent and invisible. Yet all the water of the sea has this lateral drift, including the wash-water of the breaker. The motion of the stones which it then carries is not simply up and down, but a zigzag, the general direction of which is that of the current's motion.

Where small beaches are formed on the shores of torrential rivers, small progressive waves charge in upon them; but here the current is more conspicuous than the wave, and I have then observed ripples in coarse sand facing the shore and impelled by the waves, whilst the coarse sand grains could be seen to travel much faster in the direction of the current than in that of the wave.

When, at sea, the wind is obliquely on-shore there is not only a 'longshore current, producing the effect explained above, but waves also break obliquely. Their effect to drive shingle along the shore is then obvious to the eye. On a gently sloping sandy beach the waves running directly before the wind cross the swell coming in from the offing. Just at the breaker-line they combine with the swell and cause it to break sooner than it otherwise would. Thus a number of short, oblique breakers are produced where the crests coincide, and these drive sand along the shore.

On a steeply sloping beach obliquely breaking waves are even more common and conspicuous. It is scarcely necessary to insist upon the fact that 'longshore drift due to wind will depend upon the length of fetch of the wind as well as upon its velocity, since large waves are only produced by the action of wind upon a long stretch of water.

The effect of the tides to determine the 'longshore drift of beach shingle by waves is, on the other hand, a complex matter, and it is of the highest importance that the general principles governing this effect should be definitely laid down. I will endeavour to do this for our own coasts.

Twice a day a current flows from the Atlantic Ocean into our narrow seas, and produces a rise of water-level there. Wherever the tide runs freely the currents follow the same rule as the forward and backward currents of the ordinary wind-waves of the sea, viz., when above the mean sea-level they are forward; when below mean sea-level, they are backward.

Thus, wherever the tide runs freely along a coast —*e.g.*, on a straight shore or past a headland— the current is what we may call up-channel during the whole time that the water is above mean sea-level. This means eastwards for the English

SHINGLE RIDGES.

Channel. Now, wherever there is much shingle it accumulates mostly near the highest level reached by the wash from the breakers. In such situations, therefore, most of the shingle is out of reach of breakers during the outflowing current of the tide. Moreover, for the same roughness in the offing, the breakers are very much smaller when the water is below mean sea-level, on account of the gentler slope of this part of the beach. Thus it is evident that for straight coast and for headlands the effect of the tides (apart altogether from the wind-currents and from oblique waves) is to cause the waves to transport shingle predominantly in the direction of the inflowing current, or up-channel. The predominance should be most marked in the case of the larger shingle. This predominance is independent of any excess of speed of the inflow current. Where the tide is impeded, the course of affairs is somewhat different. Thus, at the head of a bay or inlet, or where, at a nodal point, tidal currents from opposite directions have met, a "head" of water accumulates which stems the inflowing tidal current and causes the outflow to commence sooner than it otherwise would. The extreme case is that in which the outflow commences immediately the highest level is reached. In this case it is possible for the average water-level during the outflowing current to be the same as that during the inflowing current, so that the resulting 'longshore transport by waves running dead on shore may be *nil*, their effect during outflowing tide being equal and contrary to that during inflowing tide. Leaving out of account for the present the exceptional and rare positions where tidal nodes occur, we see from the above that the combined action of tides and onshore waves is to sweep shingle rapidly up-channel from all salient positions. In bays, the transport will be, on the whole, up-channel, but much more slowly, on account of the inflow and outflow currents of the tide occurring at more nearly equal levels. Thus, removal of shingle from headlands and accumulation in bays would still be general even if there were no co-operating causes, such as oblique waves and stronger currents.

Dr. Owens and Mr. Case, in their valuable book on " Coast Erosion and Foreshore Protection," have already called attention to the importance of the relation between the times of commencement of flood and ebb currents and the times of high and low water in connection with the littoral drift, and have cited the case of Southwold, Suffolk, where the upper part of the foreshore is only exposed to the flood current. I have worked out as above

THE ENCROACHMENT OF SHINGLE (SLAUGHDEN, NEAR ALDEBURGH, SUFFOLK).

the general law governing the application of their valuable suggestion.

In the case of our south coasts the general direction of the inflowing tidal current coincides with that of the greatest length of fetch and the strongest winds. Hence the effect of the above principle has been to a great extent overlooked there. Similarly, on our east coast the direction of the inflowing current is the same as the direction of the greatest length of fetch.

There is, however, one part of our coast which appears particularly suited to demonstrate the importance of the principle of high-level inflow as contrasted with low-level outflow of tide as a controlling factor in the longshore transport of shingle. This is the coast of Cumberland, as to which the following evidence was given to the Coast Erosion Commission,[1] viz., that the current of the inflowing tide is from north to south, the prevailing wind from the south-west, and the travel of beach material from north to south as far as Morecambe Bay. Even if the bare statement that the prevailing wind is south-west should need some qualification, there is no question that the prevailing westerly winds, combined with the greater length of fetch to south-west, would produce the largest waves from that quarter.

[1] By Mr. G. A. Abernethy, M.I.C.E.

Here, therefore, we have a case in which the circumstances appear to show the operation of the high level of the inflowing tidal current to be predominant against the other factors of 'longshore transport.

With regard to the velocities attained by the tidal currents on our coasts, I am not aware that it is possible to declare that those during the inflowing tidal current are, on the whole, either greater or less than those of the outflowing tide, although it would probably not be difficult to cite local cases on both sides.

There remains a peculiarity of the inflowing tidal current, or part of it, which presumably assists in the transport of shingle. This has been pointed out by Mr. W. H. Wheeler, who says that the flood tide comes along in wavelets of its own making, whereas the waters of the ebb tide are essentially calm.

I have on one or two occasions noticed the effect in a narrow channel and on tidal rivers during the inflowing current. I do not know if it lasts during the whole period of the inflowing current, or if it only continues while the level of the water is rising. I do not think we have proofs as yet that the amount of transport due to this cause is considerable.

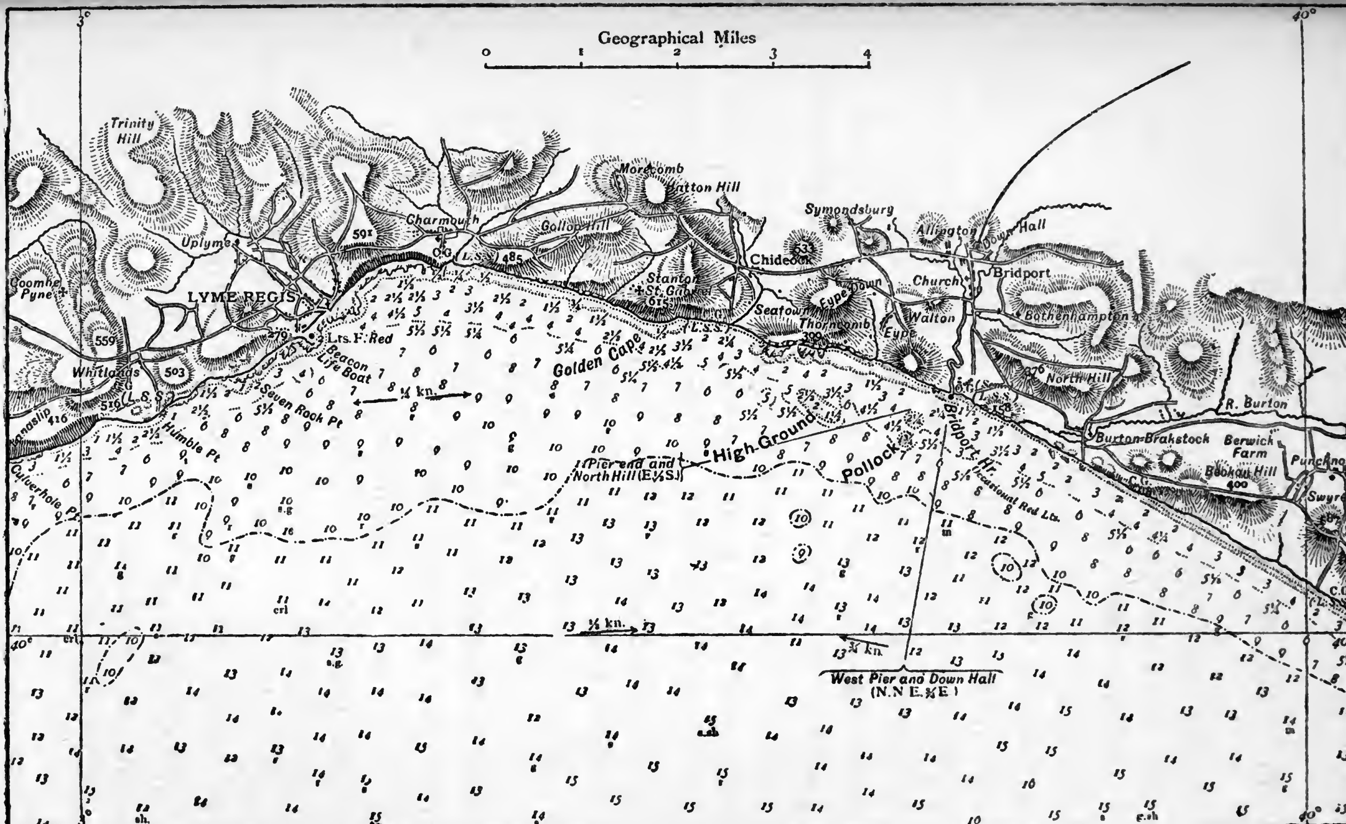
On the Causes which give rise to an Arrangement of Pebbles according to their Size along the Chesil Beach and certain other Beaches

When considering on and off-shore action of waves, we have seen that a sorting of materials takes place. It is assisted by the seaward slope of the shore. In the arrangement of pebbles along a shore there is no such gravitational assistance in sorting, except such as is given after the arrangement is effected—*e.g.*, by the greater steepness of a coarser beach. The origin of a longitudinal arrangement of pebbles on a tidal shore is therefore to be sought in the 'longshore action of the wash from the breakers during all the phases of the tide.

The effect of the action of the waves to determine the size of the shingle is, of course, best studied upon those parts of the shore where the beach is not supplied with new stones by wastage of cliffs at the back of the beach, or by a torrent entering the sea. In beaches replenished by 'longshore drift the replenishing material consists mainly of stones not easily broken into smaller fragments. The approximate permanence of such a beach, as a whole, is apt to mislead the observer into supposing the rate of 'longshore travel of individual stones to be much less than it really is. Mr. Nelson B. Richardson and I arranged an experiment upon the rate of travel of materials of which he has given a full account.[1]

On the beach opposite Fleet Coastguard Station, in a slight breeze from NNW., with breakers 2 feet high, and a current running eastwards at 1 foot per second, a brickbat, or half-brick, travelled 56 yards in 2¼ hours. Supposing this wind to remain constant, the shingle would not travel westwards even when the current is running to the west. Therefore, allowing six hours out of every twelve for the east-running current, which is less than what it is, the brickbat would then travel from Bridport Harbour to Chesilton (18 miles) in 108 days. Given strong wind from the westwards, the time of transit would be very much less. Another brickbat travelled 574 yards to the eastward in 28 hours, which would make the time of travelling the 18 miles 142 days during fine weather. A stone, 4 inches long, which was caught by a wave, appeared to move more quickly than either of the brickbats; but even if the stones were moved somewhat more slowly than the brick-

[1] "An Experiment on the Movements of a Load of Brickbats deposited on the Chesil Beach," by Nelson B. Richardson, B.A. (*Proceedings of the Dorset Field Club*, vol. xxiii., 1902).



THE CHESIL BEACH.

bats, yet the observation of the latter shows that with the ordinarily prevailing westerly winds a stone may travel from Bridport Harbour to Chesilton in a time to be reckoned in days, weeks, or months, and not in decades or centuries. When dealing with the arrangement by sizes of worn beach pebbles, we should therefore seek an explanation in the rapid shifting of the material and not in its relatively slow attrition. Thus I found the average weight of a pebble at Chesilton to be 12.8 oz., and at Burton Bradstock, 16 miles away, .028 oz.—*i.e.*, 457 times smaller. Prestwich explained this difference of size on the supposition that the pebbles travelled from Chesilton towards Burton (and Bridport), and in transit were reduced from the size seen at the former to that seen at the latter place. Apart from the circumstance that all the known agencies are to make the principal travel in the opposite direction, let us see what his supposition would involve. It is useful to consider it because of its possible misapplication to other causes where it may be less easy to disprove. In the first place, it would mean an extraordinarily short life for a pebble. In the second place, it would involve the presence all along the beach of an enormous proportion of sharp shingle-chips. My own observations lead me to think that the reduction in the size of pebbles is accomplished mainly by fracture. Although the principal pebble has its fractured surface rapidly smoothed and rounded, the sharpness of the chips tells the true tale. It is the same with wind-borne sands—the larger grains are the best rounded. If comminution really proceeded mainly by rubbing down, it would be the smaller particles which would be the best rounded.

I was fortunately able to observe on the Chesil Beach, in July, 1897, a part of the wave action by which the sorting of shingle is accomplished. I was on the beach opposite Chickerell when there was a light easterly wind, and the small breakers made by it were depleting the steep face of the beach. A glance at the map shows that wind from the east has a small length of fetch, and that the waves it makes cannot be very large anywhere on the beach, and, near Chesilton, must always be very small. The tide was falling at the time of my observation, and the shingle in the band of wet stones exposed above the waves was coarser than that out of their reach. It was evident that the backwash was removing the smaller pebbles and drifting them westwards, leaving the larger in their place.

The secret of the gradation of shingle upon beaches sheltered at one end from large waves is that whilst both large and small pebbles travel in the one direction before the big waves which come with great length of fetch, only the small pebbles are driven back by the small waves which come from the small length of fetch.

I took samples of the shingle all the way along the Chesil Beach in July, 1897 (see plate), and the following table shows their weights:

Locality.	Miles from Bridport Harbour.	Av. Weight of a Pebble in oz.	Reference to Photograph of Portions of the Samples
Cliff End, Burton Bradstock	2	·028	Group of stones on left.
Opposite Coastguard Station, Puncknowll	5	·067	Second from left.
Opposite west end of the Fleet	8	·111	Third from left.
Opposite Coastguard Station, Langton Herring ...	11	·294	Fourth from left.
Opposite Coastguard Station, Chickerell...	13	·342	Fifth from left.
Opposite "Passage" ...	16	·783	Sixth from left.
200 yards west of the Chiselton end of the beach ...	18	12·800	Last on right.

As we go eastward for the first 16 miles, the weight of the pebbles is doubled every 2 miles,

SHORE BETWEEN EAST END OF CHESIL BEACH AND BLACKNOR POINT.

STONES ON THE BEACH NEAR CHESILTON AND THE GRADATION OF STONES FROM BURTON BRADSTOCK TO CHESILTON.

but in the last 2 miles it is doubled every ¼-mile.

Most of the beach is, in fact, composed of small shingle, but close under the eastern shelter of Portland Bill the shingle is large. At the Chesilton end the beach receives new material from the steep shore of Portland. It mostly consists of large stones of the Portland stone, which is derived partly from the waste of the steep shore but not a little largely from the foot of the tips of the stone from the great quarries on the summit. It is the larger fragments chiefly which reach the foot of the tips. A glance at the map shows that large waves can travel towards Chesilton, not only from the direction of Bridport Harbour, but from the direction of Portland Bill. I found many very large pebbles of Portland stone on the beach at and near Chesilton, which must have been driven there from the coast of the promontory by these large waves. But an examination of length of fetch on the map shows at once that there can be no large waves to drive these great pebbles far along the beach to the westward. At Chesilton, or Chesil Cove, the direction of the shore changes through nearly a right angle. The Cove is open directly to the south-west. The Cove is a focus towards which large breakers can and do come in winds from north-west to, say, south-by-west, and it is a pocket into which, if a large pebble be driven, it cannot escape in either direction.

Finally, we must not omit to notice the co-operation of the tides with the eastward drift along this beach. High water on days of full and new moon occurs at about $5\frac{1}{2}$ hours at the Bill of Portland. But there is a strong outsetting current from the West Bay for 9 hours out of every 12, viz., from 2 hours to 11 hours on the days of full and new moon. This comprises all the time when the water is above mean sea-level. Thus, even such waves as do run westward along the beach (especially near Chesilton) either have the tidal current against them or else are only beating against the lower part of the beach, where much of the shingle is out of their reach.

Before leaving the interesting subject of the arrangement of beach shingle, I will give some particulars of my observations between Lyme and Bridport Harbour. Looking at the map, and at a map of the South Coast of England, we see that Lyme Bay is the largest bay on that coast, and that the sudden change in direction of the coast so as to face the south-west occurs, not at Bridport Harbour, but at Charmouth. It occurred to me, therefore, that Bridport Harbour was not the proper place from which to commence the study of the great accumulation of shingle, and I decided to supplement my observations by a visit to the shore between Lyme and Bridport Harbour. I went in a boat, rowing close under the shore, and landing from time to time. I found that the accumulation of beach material began at Charmouth. From thence to Golden Cap the size of the shingle and the height of the beach increase. Golden Cap is only slightly a promontory at high water, but there is a considerable ledge projecting above low-water mark, so that on the whole its effect as a groyne is considerable. Eastward of Golden Cap there is a curved beach as far as the promontory of Thorncombe Beacon, which again is prolonged by a ledge of rocks above low-water mark. On this piece of coast we see again the increase of height of beach and size of shingle in the angle under the west side of the promontory. Close under the east side of the promontory the sea reached the cliffs at high water,[1] but at low water there was exposed a firm bed of particles of the size of very coarse sand. This bed of material

[1] The same effect is seen on the lee side of groynes which have been built up to the highest reach of the waves, and erosion results. The groyne should be low enough to allow shingle to be washed freely over its shoreward end so that the foreshore on the lee side may be kept covered and protected.

consisted of sharp angular fragments with cutting edges, as different in shape from the sand-grains of a sandy shore as from the large rounded pebbles on the west side of the promontory. The conclusion is obvious that they were the chips from the attrition of the large pebbles on the west side, which are banged against each other by the breakers at high tide. If the current be then running eastwards, as the general information on the chart indicates, there would be a strong undertow from this position with a horizontal circulation of water on the east of the promontory. Here, except in easterly winds (which are not prevalent during most of the year), the water is smooth and the chips deposit. A true beach, where the sea does not usually reach the land at high tide, begins again at Eype mouth with very small shingle. There is no natural promontory between here and Portland, but the solid western pier of Bridport Harbour has 14 feet of water against it at high water of spring tides, and projects nearly to low-water mark. Close to the western side of this artificial promontory the shingle becomes much larger, whilst on the east side of the harbour it is again quite small. This is the situation usually reckoned as the beginning of Chesil Beach, and from here to Chesilton the shingle gets coarser

SAND BROUGHT BACK AFTER A STORM AND SAND DRIFTED ALONGSHORE.

and the height of the beach greater. The increase in the size of the shingle, however, is for most of the way a very gradual process, becoming rapid only when near the shelter of the Portland promontory.

Thus I found that wherever there was shelter from the east there was a pocket filled by a high beach composed of large shingle. The arrangement is therefore due to the normal sorting action by the waves, in which the local tides happen to assist.

I have shown why the large stones collect at Chesilton, but I must add a word on the probable mode of removal from the steep shore in that agitated corner, of the large quantity of small angular fragments which are mixed up with the boulders between the end of the true Chesil Beach and Blacknor Point. There is little trace of them on the beach at Chesilton, and the bottom off there is a good holding anchorage of clay. A strong undertow setting towards Portland is a matter of local knowledge, and Captain King's "Pilot's Handbook for the English Channel" furnishes detailed information on the subject of the outsetting current. It runs for 9 hours out of every 12 (so long does it take to relieve by a narrow stream the water from the broad bay which has piled up in the Chesilton corner), and closely skirts the rocky shore, gradually increasing in strength as it approaches the Bill, where it has acquired such velocity as to extend far beyond that point before it turns to the east. This tide out of the west bay acquires its greatest velocity when the tidal stream in this part of the English Channel is running to the eastward. While, therefore, the large shingle is driven to the focus of the waves at Chesilton, the smallest shingle, the sand, and chips are presumably removed by the undertow. What becomes of some of the material so removed is suggested in the section relating to the Shambles Shoal.

Marked gradation in size of shingle is a characteristic of beaches sheltered at one end by a natural or artificial groyne. I have not heard of conspicuous cases of such gradation on long beaches with a nearly uniform exposure—such, *e.g.*, as that at Aldeburgh in Suffolk. This being so, my explanation of the grading as due to one-sided shelter would probably have found readier acceptance but for the attractions of a previous suggestion by Sir John Coode. He noticed that a large pebble isolated on a surface of small shingle was rolled about by the wash of the waves even when this travelled over the interlocked smaller pebbles without disturbing them. He said that large stones would travel quickly along the Chesil Beach from the westwards until they reached a bed of pebbles of the large size, when they interlock and cease to travel readily; and this, in his opinion, explained the accumulation of large stones at Chesilton. The observation, as far as a horizontal current of shallow water is concerned, is correct. It is a mode of motion readily seen in fine weather, and with water of a depth of 1 or 2 inches. It is a mistake to suppose that what is then seen is a measure of the relative mobility of large and small shingle in really rough weather, and nearer the position where the wave breaks. Here, with a depth of many inches, or a foot or two, and with strong upward swirls, it is less easy to see the motion of individual stones, but there is no doubt that the smaller, loosened from their interlocking and lightened by the upward current, are driven about much more freely than the large stones. It is under such circumstances that most of the movement of shingle takes place.

What, however, I particularly wish to point out about Sir John Coode's theory of the Chesil Beach is not so much the partial truth of the observation as the logical error of supposing it to be an explanation of the origin of the observed grading.

The logical error is this, that in order that the stones shall travel in the required manner we have to suppose the stones already arranged according to size along the beach. In other words, the results of the process must be already appreciable before it can commence to operate.

The most that can be claimed, therefore, would be that the process tends to preserve an arrangement already achieved by other means, and the considerations already advanced as to the action of upward currents in stormy weather show that even for this purpose the process is probably much less effective than observation in fine weather would lead one to suppose.

On the Production and Maintenance of the Shambles Sand-bank near Portland

The great heap of sand called " the Shambles " is similar in shape and situation to the banner cloud which is formed in the eddy of air on the lee side of an Alpine peak. The Bill of Portland, projecting outwards into the currents of the English Channel, corresponds to the mountain peak projecting upwards into the currents of the air. If the promontory of Portland were removed, the Shambles sand-bank would be washed away. If, on the other hand, the sand-bank were removed by dredging, the promontory of Portland remaining, I think it is very probable that a sand-bank would re-form in the same position.

When a small vessel is taken through the race on Portland Ledge during somewhat rough weather the decks are covered with sand deposited

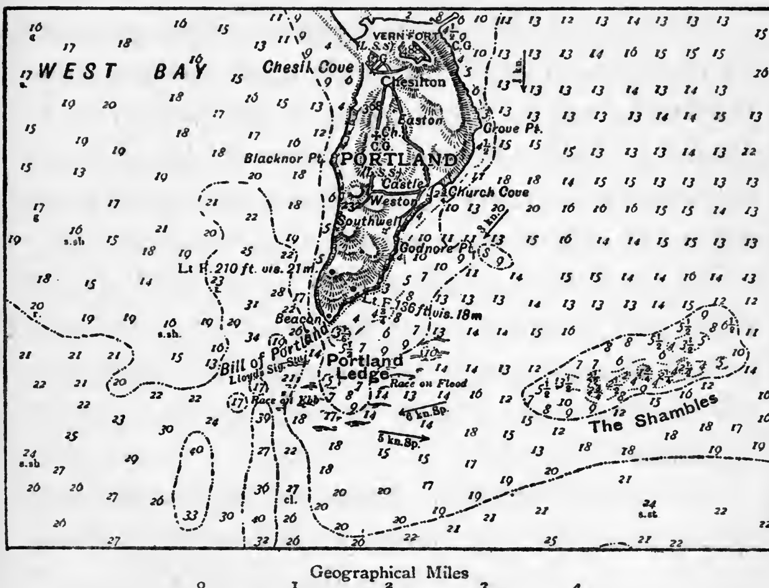


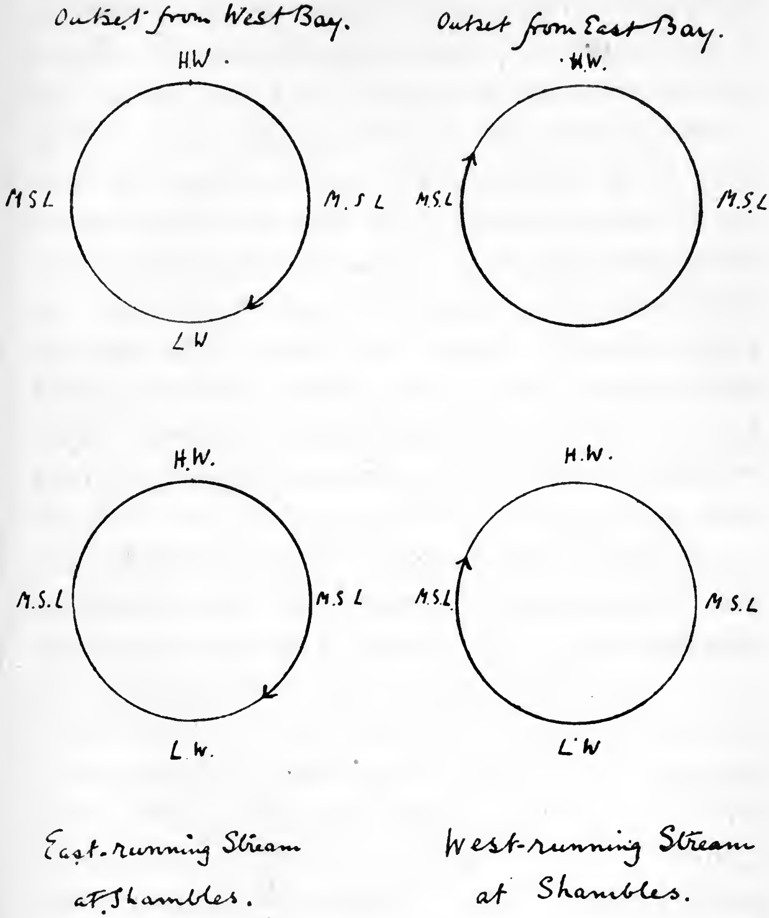
CHART SHOWING THE SHAMBLES SHOAL.

from the water which splashes over her. I have already shown that it is probable that the 9-hour outset from the West Bay removes shingle chips and sand from the Chesil Beach and the Portland cliffs, and I suppose the Shambles shoal to be maintained by this and other detritus settling from suspension in the repeated horizontal circulation of water eddying round a vertical axis on the east side of Portland.

The course of the currents is as follows:[1] The outset from the West Bay from 2 hours to 11 hours on the days of full and new moon, having assumed its eastern course, rushes with great violence over Portland Ledge. High water at the Bill occurs at about 5½ hours F. and C. (*i.e.*, on the days of full and new moon). At 6 hours 20 minutes this stream is met at right angles a short distance east of the ledge by a strong stream from East Portland Bay. This stream lasts for 9½ hours. "These united streams press on towards the Shambles, which they cross about east by north, running 3¾ knots."

The bank, which is composed of coarse sand and gravel, rises suddenly on the south from the depth of 10 fathoms. The approach on the north is more gradual. The streams run across the shoal at 3 to 4 knots during spring tides, and waves break heavily upon it. The surface is strongly rippled, and the ridges are in motion even in fine weather. The shoal does not persist, there-

[1] See "The Pilot's Handbook for the English Channel," by Commander J. W. King, R.N., twelfth edition, 1893.



RELATION OF THE VERTICAL AND HORIZONTAL COMPONENTS OF THE TIDE NEAR PORTLAND.

fore, on account of its enjoying shelter from disturbance. I suppose its maintenance to be due to horizontal circulation caused by meeting of two currents at right angles, this repetition of path giving time for the somewhat slow rate of subsidence of sand to take effect. High water at the Bill occurs in the middle of the 9 hours' outset from the West Bay, and less than an hour afterwards occurs the meeting at right angles with the outset on the east side of the Bill. Thus the presumed rotation is set up at the time of greatest wave action on the Chesil Beach, when the outset from the West Bay must be most heavily charged with sediment.

The outset from the East Bay of Portland presumably contributes sediment to the Shambles when the main tidal current is setting to the eastward. The tidal current sets westward at the Shambles at about 11 hours F. and C.—*i.e.*, about the time of low water and at the time of cessation of the outset from West Bay. The outset from the East Bay is then running, and continues to do so for another 5 hours—*i.e.*, until 4 hours F. and C. That no shoal corresponding to the Shambles is formed by the west-flowing current on the west side of Portland Bill is to be ascribed largely to the lower water-level and consequent lesser wave action on the shores.

In this connection the position of the Skerries Bank, north-east of Start Point, should be compared with that of the Shambles. Portland Bill terminates, on the eastern side, the largest bay on our south coast. Start Point similarly terminates the second largest bay. On the up-channel side of each is a sand-bank, which, from its situation, and from the absence of a corresponding bank on the west of the promontory, suggests rather the continuous current of a river than the alternating currents of the tides. Of all the causes which produce this curious arrangement the relation of the time of turn of the tidal stream to the turn of the tidal level is, perhaps, the most important and the most likely to escape notice.

The accompanying diagrams show the relation between the times of the vertical and horizontal oscillations of the tide at Portland Bill.

The Formation of Patches of Shingle upon a Sandy Beach by the Action of Breakers

The surface of the beach at Branksome Chine is usually pure sand, but many stones derived from the wasting of the gravelly cliffs are buried beneath it. Under certain conditions the wash of the breakers begins to convert the sandy to a shingly beach, and the action often proceeds as far as the formation of isolated patches of shingle.

The occasion upon which I saw the process proceeding best was during a heavy swell succeeding a storm, when the wash of the breakers carried the sand away in suspension. The shingle remaining behind became concentrated in the manner illustrated by the photographs. The plate facing p. 214, from a photograph, taken on a later occasion, and about 4 miles farther east, shows more distinctly the characteristic wedge-shape of the isolated patches of shingle. If the process were to continue, these patches would coalesce into a single ridge of shingle. This sorting action of the waves is at once taken advantage of by builders or others requiring shingle, carts being sent to remove it before the smaller waves and offshore winds have again smothered it with sand.

SHINGLE SORTED FROM SAND BY THE WASH OF A HEAVY SWELL
(BRANKSOME CHINE, NEAR BOURNEMOUTH).

REMOVING SHINGLE AFTER A HEAVY SWELL, BEFORE THE SAND IS BROUGHT BACK IN CALMER WEATHER.

CHEVRON-SHAPED PATCH OF SHINGLE FORMED BY THE WASH OF THE SWELL ON A SANDY SHORE (BOSCOMBE).

PART III

ON STATIONARY AND PROGRESSIVE WAVES IN RIVERS

CHAPTER VII

The flood-wave of rivers—The roll-wave in the Tees—In the Ure—In the Nikko torrent—On the advance of a flood over dry ground.

On the Flood-waves of Rivers

A PROGRESSIVE wave is not an obvious phenomenon in ordinary river floods; nevertheless, a careful consideration of the matter shows that wave-transmission is an important factor in the disposal of the flood-water of a river. Let us take the case of a river receiving an accession of water from a suddenly swollen tributary. The threatened congestion of water is avoided by wave-transmission down the main stream. The length of the wedge of newly added water is sufficient to originate a "long" wave, and the wave-velocity down-stream is therefore the greatest that is compatible with the depth, viz., the velocity which a body would acquire if falling *in vacuo*, under the action of gravity, through a height equal to one-half the depth of the stream. If the calculated velocity of a " long " wave in different depths of water be compared with the observed velocities of current in large rivers, it will be seen at once that the wave-velocities are many times greater than the velocities of the currents. Thus the flood-water obtains room for itself, not so much by rushing forward as by causing the waters for a long way in front to lift or swell slightly. The transmission of pressure through the current is so rapid that there is (except under special circumstances, to be described later) no visible wave, but the river lower down is found to be rising long before the arrival of the floating and suspended matter which accompanies the arrival of the actual waters of the flooded tributary. The speed at which this wave-transmission of the flood progresses down the channel is equal to :

Velocity of current *plus* velocity of " long " wave.

In the case, however, of a shrunken river flowing through alluvial soil the rate of advance of the " first rise " of water after a drought may be much diminished by the absorption of water by the porous ground over which the river has to spread.

When a river increases in depth in its lower reaches, the wave-velocity increases, and the amplitude of the wave is thereby diminished, and the increasing width of the river further diminishes the amplitude of the wave. Thus the very perfection of the mechanism of wave-transmission down-stream in rivers usually prevents the accumulation of a wave-face sufficiently steep to be visible. The rise of a river before the arrival of the actual flood-water which originates the rise is, moreover, less obviously wavelike in character than the rise of level in a river due to the tide, for in the former the rise is accompanied by increased velocity, just as it would be if the river were running at a steady, but higher, level. In the case of the first rise of a river due to tide, however, there is a slackening of the current.

We see, therefore, that causes commonly co-operate to mask the progressive waves due to floods in non-tidal rivers.

In the upper reaches of certain rivers, however, the sudden arrival of a wall of water, travelling down-channel at a great speed, is a normal occurrence after heavy rain in the hills where the river and its tributaries take their rise. Thus, on the River Tees, during one summer and autumn the roll-wave, as it is called, was seen on no less than six occasions by Mr. F. R. Glyn, F.R.G.S. The following description of the phenomenon is taken from a letter written by Mr. Glyn to the author, January 14, 1902:

"This river [the Tees] has its source at the foot of Crossfell, in Westmorland, and with a considerable watershed is fed by mountain streams and a number of tributaries between Middleton and Crossfell, running through the extensive moors in that district.

"One of the peculiar characteristics of this river is the roll-wave, 2 feet or 3 feet high, which suddenly, and sometimes quite unexpectedly, comes down the river, filling from bank to bank the stream, which but a minute previously had, perhaps, been at low summer level. Many lives have in consequence been lost, while I personally experienced a most unpleasant sensation some years ago. I happened to be fishing for salmon from a dry rock in the centre of the river, some few miles below Barnard Castle, when I suddenly heard a rushing noise, as if the wind had suddenly risen and caused the branches of the trees to rustle. I looked up the river and saw the roll-wave almost upon me. Before I could get to land it had washed me several yards down, and but for a side stream that, fortunately, brought me to land, I should not have been able to record the facts. As it was, I lost my salmon-rod, cap, &c., but was most thankful for such a providential escape.

"It is at all times a naturally rapid river, winding its way over large masses of rock and boulder, and the most accomplished swimmer would have but little chance of saving himself.

"In the neighbourhood of Barnard Castle, a few miles below that town, we generally allow seven hours for the river to come down after rain in one's locality; and such calculations are very near the mark, but, of course, occasionally after heavy thunderstorms above Middleton and otherwise the wave descends without any warning whatever to anglers and others in the lower districts. As there is sometimes an entire absence of rain locally, these sudden and sometimes unexpected spates make the Tees in summertime dangerous even to the most experienced."

The Ure is somewhat similar in general character to the Tees. At Aysgarth it is well known to lovers of the picturesque on account of the beautiful Fall, or "Force." The pavement-like rock bed of the river outcrops horizontally, and the depth of the river is fairly uniform in cross-section, although longitudinally it consists of pools and shallows. The Tees also, where I have seen it near Barnard Castle, was of uniform depth (crosswise), owing to the nature of its bed of hard and homogeneous rock. I may note in passing that uniformity of depth across the stream is important for the preservation of a roll-wave. In a channel with deep longitudinal grooves and shallow shores such waves would change their direction and discharge laterally upon the shelving banks.

I have received the following account of the roll-wave at Aysgarth from a resident at that place:

"The Aysgarth local name for a flood was 'spate' or 'freshet.' I was one evening in the middle of the river, about 100 yards below the lower Force, fishing, when I heard a roar above, and presently a wall of water some 2 feet or 3 feet high came dashing over the fall. I, fortunately, gained the bank in time to see it rush past me, filling the bed, rushing madly over the boulder rocks, and spoiling my fishing. The rocks here are limestone, with great fissures and pot-holes. Below the Force is the great salmon-hole, the limit of the up-rushing fish.

"Above the lower Force the stream runs in reaches over shelving limestones from the second Force. At the foot of this there is a very deep hole. . . . Succeeding this Force the water comes beneath the picturesque bridge from the beautiful upper Force, a succession of ledges, forming holes beneath."

The arrangement of a river in alternating pools and shallows is a condition theoretically favourable to the formation of such roll-waves as are described by these observers. The wave-velocity diminishing greatly where the bottom rises at the lower end of the pool, this section at first receives far more than it can pass on, so that the wave face, instead of being of infinitesimal gradient, becomes quite steep — a "wall" of water in appearance.

On entering a pool the wave may perhaps lose this form, commonly called a bore, and become a group of rounded swells, but on entering shallow water this will close up, and the front of the disturbance will be either a cusped wave, like a wave about to break upon the shore, or a solid wedge of foaming water—the bore proper—like those beautiful foaming ridges which come in upon a flat sandy shore when the great waves of a storm are breaking far out at sea.

Roll-waves are also reported as occurring in the Rhondda and the Taff Rivers in Wales. They are frequent in the rivers among the foothills of the Himalayas. They are also recorded from time to time as the result of an exceptional and solitary cause of flood in various parts of the world. Thus, during the great typhoon in the autumn of 1902 a landslide from Mount Nantaisan in Japan caused a sudden efflux of water from Lake Chusenzi, which, combined presumably with the torrential rain, caused a wall of water many feet high to travel down the Nikko River, doing great damage to the celebrated Thousand Statues of Buddha on the right bank. Its speed was certainly very great, judging from the account which I received from the Japanese custodian of a tea-house on the right bank, which was at once swept away. The man himself had only just time to scramble up the hillside, although the situation allowed him a clear view for a considerable distance up-stream. The high-water mark of the flood was still visible on the hillside when I visited the locality a year afterwards.

In the account which Sir Samuel Baker gives of the coming down of the waters of the Atbara (*vide* "The Nile Tributaries"), the bed of the river appears to have been dry except for entirely isolated pools of large extent. The occurrence was at night, and no details are given of the appearance of the actual front of the flood as it advanced over the dry bed. The advance of the floodhead in such a case is not a simple case of wave-travel to which a definite speed is allotted in the theory of long waves, dependent upon the depth of water, for there is no water in front of the advancing wedge. The rate of encroachment would, in the above case, be somewhat reduced by the porosity of the soil over which the flood advanced.

Colonel Gaillard, U.S.A., informs me that he once saw the wave-front of a flood advancing along the dry bed of a canyon in Arizona. He estimated the depth of water at the crest of the wave at 25 feet and the horizontal distance from the advanced foot of the wave to this crest at about 300 feet. This space presented a series of frothy ridges. Perhaps these were a series of roll-waves over-riding one another. The mechanism can be imagined from that described later for the roll-waves of the Grünnbach conduit, where the larger waves, *i.e.*, those which have deepest water at their crests, continually overtake the smaller ones.

CHAPTER VIII

Tidal bores—Wave-length of the Severn bore—On the want of concordance between height of tide and height of bore, and on the conditions which determine the starting-point of the bore.

On Tidal Bores

THE time during which the tide flows in a river is less than that during which it ebbs, for during the flood tide the river quickly gathers an opposing " head " of water (both on account of the slope of its bed and of the diminution of its breadth) which reverses the tidal flow, so to speak, before its time. Conversely, the form of the channel as well as the momentum of the land water, or true river water, prolong the seaward flow of the ebbing tide. If the conditions be considered at different places successively farther up the river, it will be seen that this difference increases, the duration of flood tide being less and that of ebb tide greater at places higher up than at places lower down the river. When we reach the limit of tidal influence of the river the duration of flood tide is, of course, zero, and ebb goes on all the time. The phenomena are too extended in a horizontal direction, and the surface gradients of the water are, for the most part, too small for the eye to see the ebb and flow of the tidal river as a wave; but in a diagram, with the vertical scale much exaggerated, showing in profile the advance of the tide up the river, it appears in the form of a travelling wave, which becomes steeper as it advances up the river. If the course of the ebb tide down the river be similarly shown on a diagram, it will be seen that the front of the wave is never so steep as the front of the flood-tide wave becomes in the upper reaches of the tidal river. This is partly because at the commencement of ebb the river is full and the water deep, instead of being at its shallowest as at the commencement of the flood.

In many tidal rivers a visible wave with a very steep front, travelling up-stream, constitutes the "first rise" of the flood tide, which is sometimes referred to by boatmen simply as the "head" of the flood, but it has also specific names, such as the "Bore" and the "Aegir" (on the Trent). This phenomenon has long been accepted in works which deal with the theory of tides as being the steep face, or the steep part of the face, of the flood-tide considered as a single wave, although Sir G. H. Darwin has pointed out that theory serves rather to explain a rapid rise than an absolutely sudden one.

In the account which I have now to give of the tidal bore, as I have seen it in the River Severn, it will be found that it seems to have a wave-length insignificant in comparison with that of the tidal wave considered as a whole.

Wave-Length of the Severn Bore

The River Severn, which is tidal up to and beyond Gloucester, pursues below this city a sinuous course, similar to that of a non-tidal river in an alluvial plain. The gradient is at first slight, and the chief peculiarity of the bed is the occurrence at several places of ledges of rock lying across the stream, which suddenly reduce its depth. Thus the depth at ordinary low water over the "Stonebench" is 3 feet, whereas the depth in the long pool below is 10 feet. Denny Rock is another shallow, which has a deep reach above it. The character of the river changes somewhat near Priding, where sand-banks begin to be prominent at low water. Between Gloucester and Priding is the best part of the river for viewing the bore,

THE COURSE OF THE RIVER SEVERN FROM GLOUCESTER TO THE SEVERN TUNNEL.

if the object be to see an imposing spectacle. The favourite spot, visited by crowds at the highest tides of spring and autumn, is Stonebench, and there are others similar to it, such as Denny Rock. The phenomenon at Stonebench is very striking.

The wave slackens in speed when it comes to the shallowing water, increasing in height the while, and finally charges over the shoal with a rush of broken waters. I saw the phenomenon at Denny "Pill" (or Brook) on April 30, 1900. Here the wave, when first seen, was already in shoal water, and, at all events from my low point of sight, appeared solitary. It had a steep front, in places overfalling upon itself with foam (see Plate). As soon as it passed the place of observation it presented another appearance, viz., that of a group of smoothly-rounded waves (see Plate). Being on this occasion closely occupied with obtaining photographs, I did not observe this part of the phenomenon with undivided attention; but on a subsequent occasion (October 30, 1901), at Priding, I was able to observe carefully, and to photograph, a similar occurrence. The approaching bore, whatever wave disturbance may have been half-concealed behind, presented a face like the breaker of the seashore, and this was almost all that was noticeable from the front. But when the bore came opposite to me, the water being deeper below the part of the bank on which I stood, the steep, bold front was gone in an instant; a rounded wave or swell, followed by others of the like size and form, being immediately substituted, and the number of these swells rapidly increased, the group lengthening to leeward, so that in a few seconds I counted no less than sixteen of these large swells,[1] forming a group of waves of remarkable appearance, which progressed, as a whole, with singular slowness, owing, I suppose, to the well-known circumstance that the speed of a group of waves (at least in deep water) is only half that of the individual wave. The above observation suggests important reflections upon the nature of the tidal bore. This term is by common consent employed to designate a steep-fronted wave, either overfalling or on the verge of breaking, constituting the first rise of the tide in a river or estuary. If it be actually a part of the

[1] These are often referred to as "ripples," but the etymology of the word indicates the propriety of restricting its use to little waves. Its use for waves of capillary size, as proposed by Lord Kelvin, may be conveniently extended in the case of other materials—*e.g.*, sand and snow—to a small class of waves only affecting superficial strata, co-existing with larger waves capable of indefinitely great development.

THE BORE ON THE SHALLOWS OF DENNY ROCK, AND AFTER REACHING DEEPER WATER.

face or front slope of the whole flood tide regarded as one wave, then its length is indefinitely great as compared with the depth of the Severn at Priding, and the only change on entering slightly deeper water would be an increase of speed, accompanied by diminution of height and, perhaps, of steepness. There would be no resolution into a group of waves. It appears, on the contrary, that the greater part of the (no doubt complex) wave which was seen to approach Priding was "long," as regarded the shoal water, but "short" as regarded the deeper water.

From Priding or Framilode to Hock Crib, or Hock Cliff, as it is also called, is the last great horseshoe bend of the permanent banks of the Severn. Below Hock Cliff are the straight diverging banks, with a straight axis, which indicate the subordination of fluviatile to estuarine conditions. Already in the stretch from Framilode, past Newnham at the apex of the horseshoe bend, to Hock Cliff, we see the near approach of estuarine conditions in the rapid divergence of the banks, and in the sand-banks, dry before low water, which are here a feature of the river.

The bore at Newnham is a less imposing wave than in the narrower river from Denny to Stonebench, where the whole width of the channel is filled even at low water, and the bore, besides being much higher than at Newnham, reaches from bank to bank, and seems as if it would overwhelm everything in its course. Nevertheless, convenience of access, and the wide prospect of the river from the lovely Newnham churchyard, situated on a salient bluff at the bend in the river's course, combine to make this a favourite spot for viewing the approach of the bore. The first appearance of an advancing line of foaming water far down the river below Awre, at a distance of some miles, is indeed a most impressive sight.

I first saw the approaching bore from Newnham at the high tide of April 29, 1900. Having descended to the ferry, I entered a boat and surmounted the wave just outside the projecting cliff, which makes a kind of harbour at the ferry. There was no change noticeable in the current when the boat rose to the bore, in the deep water, but after it was passed the boatman almost immediately brought the vessel to land with a few strong strokes, in order to avoid the tremendous current which quickly succeeded the passage of the wave.

The wave was not solitary, for after it passed the water flowed back from the shore, exposing many yards of tabular rocks which it had covered. It then surged up again, and during the rapid current above referred to the rise of level was continuous.

The second occasion on which I saw the bore from Newnham was on October 29, 1901, after a summer when the river had been low owing to small rainfall, and at a time when the usual heavy rains of autumn had not commenced. Although the tide was almost the highest of the year, the bore was a very small one. Stationing myself first in the churchyard, I noticed that the bore, which had been visible before entering the pool near Bullo, disappeared there except for some disturbance of reflection from the surface of the deep water. I then ran down to the shore. On the shelving sand-bank which formed the left shore of the low-water channel the bore advanced as a crested wave of no great size, rolling over upon itself. As I watched this, my attention was caught by the sudden submergence of a stake near me, which I had noticed as being convenient for marking if there were any change of level before the arrival of the bore. I found, however, that the quick rise of water which covered the stake was the whole of the "bore" on this, the deeper, side of the river. There was here no steep-fronted wave. Moreover, after this rise, there was a marked subsidence, so that the wave was not solitary. I obtained two photographs showing the level of the water when the bore was passing, and, a few seconds afterwards, during this subsidence.

On the Want of Concordance between Height of Tide and Height of Bore, and on the Conditions which Determine the Starting-point of the Bore

The capricious character of the tidal bore is one of the most interesting characteristics of this phenomenon in the Severn, and I suspect that it is capricious in other rivers also.

The disturbing cause lies in the sand-banks below Hock Cliff, and we will therefore now describe the character of the river or estuary below that point. The change which there commences is not only that which has been mentioned —the straight, diverging banks of the high-water channel, in place of winding, nearly parallel banks —but also a change of gradient. The low-water slope, which from Gloucester to Framilode is slight, becomes very steep below Hock Cliff, and continues of unusual steepness to the Sheperdine Sands. Below the Severn Bridge, which practically bounds the view down-stream from Hock Cliff, the steepness is slightly increased. Below the Sheperdine Sands to Aust the low-water gradient is again slight.

THE NOOSE SANDBANK

It is between Hock Cliff and the Severn Bridge that the bore usually commences, according to all testimony. The river at low water below Hock Cliff continues to flow in a single channel, the position of which, however, is no longer fairly constant, as at Newnham, but depends greatly upon the quantity of land water. After a wet season it hugs the left bank, cutting a deep trough in the loose sands, and making as wide a bend as the permanent bank permits. This is the condition which, according to the testimony collected by the late Frank Buckland [1] and also by myself, gives rise to a large bore at Newnham, about four miles farther up.

In dry seasons the channel, which contains all the water during most of the time of ebb and during the commencement of flood, lies much farther from the eastern shore, taking a straighter course. Presumably in this as in other cases which I have noticed elsewhere, the shorter course is due to the influence of the flood tide, which tends to flow in a chord of the arc made by the ebb, or river current.[2] After the dry season of the summer of 1901, the ebb was flowing in such a channel, far from the eastern shore and between perpen-

[1] "Log-Book of a Fisherman and Zoologist," 1875.

[2] *Geographical Journal*, August, 1901: "On Sand-waves in Tidal Currents."

dicular cliffs of sand. When, at 8 a.m. on October 30, 1901, I stood in the slime at the foot of Hock Cliff, I saw the bore advancing from beyond Awre as a line of white breaking water, stretching quite across the channel, its summit being lower than the top of the cliffs of sand. The height of the wave seemed to be about 2 feet or 2½ feet. To the left of where I stood commenced the now disused channel following the east, or Frampton shore, which lower down became a deep trench. At 8.10 a.m. the bore, having reached the upper entrance to this channel, sent a wave swinging round to the east into it which travelled down as a bore, while the main bore passed me at 8.13 a.m., much diminished and enfeebled, on its way to Newnham. That the bore at the latter place would this morning be a feeble affair, as had been the case on the preceding evening, I could well believe when I saw how the "head of the flood" was squandering itself in driving another wave and stream of water down the Frampton Channel. Indeed, the fishermen tell me that sometimes a bore coming up this channel meets that which I saw travel down it, and that a boat which finds itself between them is in a dangerous predicament. At 8.35 a.m. I saw a small bore travelling across the sandbank which separates the Frampton Channel from the present, or Awre, channel travelling up-stream, and from the Frampton towards Awre Channel, which was not yet quite full. The arrival of this reinforcement completed the covering of the sandbanks, and a broad sheet of water lay stretched before me from shore to shore. At 8.39 a.m. the water was slack, or nearly so, and then commenced to flow up-stream towards Newnham, but no longer with a "head." Thus the first flow was retarded 26 minutes. The total rise of tide at Newnham would probably be lessened not at all, or very slightly, by the circulation which took place between Frampton and Awre.

As has been said, the Severn bore actually commences somewhere between Severn Bridge and Hock Cliff, according to concurrent testimony. Below Severn Bridge it is reliably reported that a bore sometimes makes an appearance in one or other of the low-water channels between sand-banks, but it vanishes again. Yet the low-water gradient of the river is not less, but rather greater, below Severn Bridge, and the rate of progress of "first rise" of tide from the Sheperdine Sands to Sharpness (a little below Severn Bridge) is even slower than from Sharpness to Hock Cliff. Why, then, does not the permanent bore originate between Sharpness and the Sheperdine Sands, especially as it is not far below this that there is the greatest tidal range (about 40 feet at springs)? It may occur to the reader that a long run is required under bore-forming conditions before the bore becomes appreciable; but both theory and observation show it is not so. If the conditions for forming a bore be fulfilled, the wave attains a considerable size in a very short interval both of time and space.

An answer to the question, Why does the bore usually originate above and not below Severn Bridge?—*i.e.*, in the upper, not the lower, half of the steep slope of the estuary—is afforded by the following observations made from the commanding elevation of the Severn Bridge (100 feet above low-water mark), on April 27, 1900, two days before the highest of this set of spring tides. At 3.43 p.m. the approach of the flood tide could be discerned by a change of appearance of the water, although there was no actual surface wave. It was 4.5 p.m. before the level of the water was rising at the bridge, so slow is the advance of the first rise. I was stationed near the west end of the bridge, where the principal low-water channel of the ebbing water lies. The flood tide did not force its way up this channel against the strong stream, but was pressed away towards the east, filling a swatchway, or blind channel, which led away to the east of a sand-bank called the Wave-ridge, or Waifridge. After working thus to its right until 4.30 p.m., with slow current but rapidly rising level, the flood tide, having filled the swatch-way brim full, suddenly swept over the Waifridge Sand in a broad sheet of water, which poured over to the westward into the main channel.

The sands, which had been drying for several hours, were covered so suddenly that the imprisoned air spouted through the seething water.

It is evident that the presence of an alternative channel, open from below, prevented the formation of a bore in this case, just as at Hock Cliff the alternative channel, open from above, reduced the bore after it had been formed.

The flood tide goes the way of least resistance, and if it be free to circulate, it does not stem the ebbing stream and form a bore. The presence of alternative channels, which becomes more marked as we travel down-stream from Severn Bridge to Sheperdine Sands, is in itself sufficient to explain the non-formation of a permanent bore in the lower portion of the steep slope of the estuary.

Near Beachly Point, just below the foot of the steep slope to which I have so frequently referred, I watched the commencement of a spring tide on April 28, 1900. The first rise was perfectly calm, being unaccompanied by any wave or other commotion.

It remains to explain why the flood tide, at its first rise, preserves alternative channels in the lower part of the steep slope below Severn Bridge and not in the upper, or only to a limited extent, for on the absence of side channels depends the possibility of forming a bore where the other circumstances (shallowness and a fairly steep gradient) are present.

The sands which encumber the bed of the Severn from Hock Cliff to the Sheperdine Shoal are subject to arrangement and redistribution alternately by the waters which flow seaward and by those which flow landward. In the upper part of this region the sands are arranged so as to form a channel almost like that of a non-tidal river flowing in an alluvial plain. Particularly is this the case when the land water much predominates, as during neap tides and after heavy rains. The ebbing stream, flowing continuously for many hours in its narrow winding channels, continually lowers its bed, scouring the sand from beneath and forming a channel which, at the time of first rise, has high, steep banks. The first rise of the flood tide has therefore, as a rule, to make its way against this ebbing stream up the normal river channel which has been prepared for it. Then the bore is produced, and it is noteworthy in this connection that, according to the observation kindly communicated to me by Mr. D. Wintle, of Newnham-on-Severn, the bore is more marked there at the commencement of spring tides than after they have been running for some days.

In the lower reaches of the steep slope, and above Beachly Point, the land water forms a smaller proportion of the total, and the duration of the ebb is shorter. The sands, as they are at low water, are therefore not arranged so well to facilitate the run of the ebbing waters, their distribution, on the contrary, exhibiting certain features markedly favourable to the commencement of an upward flow. This change of conditions exhibits itself by the presence of swatchways, or by-channels, such as that above referred to.

How these are formed has been already indicated, and may now be further explained. The ebbing stream ponds back the flood, which consequently makes another way for itself through and across the sands. The relation of the two classes of channel due to ebb and flow respectively has been described by the author elsewhere.[1] Briefly, the low-water ebb channels are narrow, deep, and

[1] *Geographical Journal*, August, 1901.

sinuous, those of the flood broader, shallower, and straighter. Tidal bores appear to be characteristic of rivers where there are drying sand-banks, and are perhaps only produced there in a part of the sandy estuary which has not yet settled down to a permanent form. The bore marks a struggle between flood or ebb which appears to be a transitory state of things, for in Professor Osborne Reynolds's model estuaries the bore disappeared in all cases when the sand-banks had attained their final form.

From the above it appears, when we study on the spot the conditions of a tidal bore as exhibited in the River Severn, that the phenomenon is somewhat more local and less general than the usual mathematical treatment of the subject would lead one to expect. The visible wave is not the steepening of the front of the tide as a whole, but the steepening of the front of the rising water in a short reach of the river. The observation above recorded of the multiplication of the wave on entering the water of moderate depth supports this view.

The tide presumably does not make its way steadily up a tortuous channel, its progress, on the contrary, being alternately checked and hastened. Even on an open coast the rise of the tide, as registered on the gauges, is markedly pulsative, the curve presenting "notches." These are a marked and disturbing feature of the records of tide-gauges, and positions are consequently chosen for their erection on the coasts where the uninterrupted run of the tide shall cause them to be as slight as possible. This pulsative rise of the tide is sometimes strikingly visible to the eye in situations where there is a considerable inflow over nearly flat sands. Thus, on the Anat sand-bank, on the left shore of the river mouth at Montrose, N.B., where I was standing at the turn of the tide on March 17, 1900, the water came suddenly rushing in, filling up the hollows and threatening to cover the whole area. The rush, however, soon ceased, and the water then receded, leaving the sands bare once more; but only for one or two minutes, when another rush again occurred, and I do not think that the water subsequently retired.

In subsequent observations on the Severn and elsewhere it will be well to look out for this process, especially at places below the point of starting of the regular bore. It may be that these considerations help to explain the absolute suddenness of rise which constitutes the bore, and which, according to Sir G. H. Darwin, is not quite what is indicated by theory—that is to say, by the theory which regards the bore as the face of the tide-wave considered as a whole.

CHAPTER IX

Cinematographing the Severn bore.

In 1901 Mr. Charles Urban very kindly lent me a bioscope camera and the services of an operator for the purpose of cinematographing the Severn bore. The photograph was taken under my direction on September 29, 1901, and was shown at the meeting of the Royal Geographical Society on November 25th. I believe this is the first cinematograph of a tidal bore.

The cinematograph picture was taken at Stonebench, below Gloucester, which is distant 4 miles by road, reckoning from the cathedral. The tide was the third after full moon, and was not quite so high as that predicted for September 30th, which was one of the four highest predicted tides of the year. After the dry summer the amount of land-water in the river was probably below the average, nevertheless, the low-water level was 1½ feet above that given as summer low water in Admiral Beechey's survey made in 1849. The

CINEMATOGRAPHS OF THE BORE APPROACHING STONEBENCH.

reason, no doubt, is that the spring tides had already begun to fill up the river. The camera was placed upon the left bank, as low down as was consistent with the safety of the instrument, and about 30 feet back from the submerged " Stonebench," so as to show the breaking of the wave where the water suddenly shallows from 6 or 7 to 2½ or 3 feet. A boat was engaged to meet the bore, and was anchored in deeper water at a suitable distance; and to obtain the scale a post near the left bank was measured, its top being found to be 58 inches above low water.

The bore was heard at 9 a.m., a few seconds before its appearance round the bend of the river, at a distance of 513 yards from the camera. The resurgings from the concave left bank had a fine effect, well reproduced when the film is shown upon the screen. The boat rode easily over the unbroken wave in about 10 feet of water. The height of the wave there I estimated at from 3 feet to 3 feet 6 inches, and the height at the sides of the river 4 to 5 feet. At the jetty or breakwater, of which one post already referred to was visible beyond the osiers, the bore suddenly sent a sheet of water up to a height of 7 or 8 feet, but, recovering itself in a moment, the wave came on with a front still smooth and unbroken, its inverted image perfectly mirrored by the smooth water ahead of it. Then, on reaching the hidden Stonebench, the wave curled over in a beautiful scroll. But no stationary photograph can reproduce the effect which is given on the screen as the dark-fronted curling wave rushes out of the picture, which is then immediately flooded with light, the bright clouds instead of muddy banks being now reflected by the smoother waters. The speed of the bore was about 13½ statute miles per hour. The exposure of film was continued after the bore had passed in order to illustrate the after-rush of water, the speed of which was well shown by floating debris. A boat happened to come by, one of the occupants of which was gathering flotsam and jetsam, and the camera was then revolved so as to follow the boat as it passed. Owing to high osiers intercepting the view up-stream, it was not practical to cinematograph the bore from behind, as had been intended. High water occurred 56 minutes after the passage of the bore, the total rise being 8 feet 6½ inches. The height of the water then above ordnance datum was several feet higher than high water of even a 40-foot tide at Portishead. The current continued to flow up the river for 31 minutes after high water.

The tidal bore in nature is not precisely repeated

CINEMATOGRAPHS OF THE BORE ON REACHING STONEBENCH.

at succeeding tides, and in most rivers is not seen at every tide. The cinematograph representation, on the contrary, can be repeated on the screen as often as required, and with a delay of only one or two minutes while the film is being re-wound. At each repetition the observer can concentrate his attention upon one particular feature. In this way I have seen several things on the picture which escaped my observation on September 29th. Measurements can also be made from the film, either in the hand or from its projection on the screen.

Description of Plates.

(*The figures are enlargements from individual pictures upon the cinematograph film.*)

Fig. 1 shows the bore in the distance as a bright band, where immediately before had been the dark image of bank and trees. The 5-foot post is visible on the left, with its reflection below.

Fig. 2 shows the boat rising to the wave. The wave on the right of the boat cuts into two the reflection of the trees on the right bank. A comparison with Fig. 1 shows at once the turbulence of the water behind the bore. The alternation of wide bright bands with narrow dark bands parallel to the front of the bore indicates the character and position of the undulations behind it, whilst the confused reflection of light near the left bank indicates resurging therefrom. If the apparent heights of the banks in the two figures be measured, the level of the water will be found to have risen behind the bore.

Fig. 3 shows the wave as yet unbroken, but with steeper front, due to its approach to the shoal ; the inverted image is plainly visible. Measurement of the post from the picture shows that the water there is 2 feet 5 inches above the level of the river in front of the bore.

Fig. 4 shows the bore rushing over the Stonebench. The mean level of water at the post is 2 feet 11 inches above low water, but there is a noticeable difference of level at front and back of the post, indicated by a dark shadow on the picture. This shows that the current, which, shortly before the bore arrived, I found to be ebbing seawards at 0·8 mile per hour, is now making in the opposite direction with considerable strength. The boat remains in position, being anchored.

BORE VIEWED FROM BEHIND AFTER PASSING STONEBENCH.

CHAPTER X

Stationary or standing waves—Cross-stream progressive waves : observations in Niagara River.

Stationary or Standing Waves

ONE who observes the well-known waves of rapid, or rock-encumbered, rivers from the bank cannot fail to notice that whereas the shape of the corrugated surface is not very different from that of an agitated sea, yet there is this great difference, viz., that the river-waves maintain their position unchanged; and, partly for this reason, they are called stationary or standing waves. If a piece of stick be tossed upon the stream, its downstream motion over the corrugated surface will be seen to be alternately checked and accelerated as it reaches the crests and troughs respectively. Mathematically, this undulated river is regarded as a steady stream, flowing, say, to the right, with a train of waves travelling to the left at a speed equal to that of the stream.[1] This conception will be found very helpful to a proper understanding of the subject; and that it is no mere subtlety of thought is realised immediately by one who shall drift in a boat through such a train of waves. Dropping down-stream in this way on the ebbing tide between the piers of the Severn Bridge opposite Sharpness, my eyes were fixed upon the waves which combed over towards me. Almost at once the sense of drifting vanished, the boat seemed no longer to progress through rough water, but, on the contrary, to be at a standstill, whilst wave after wave charged past her.

In small streams it is not difficult to produce stationary waves by introducing a stone or boulder, or, better still, a transverse barrier which rises above the bottom sufficiently near to the

[1] An excellent illustration of a wave with a motion equal and opposite to that of the current is seen when one pours water into the centre of a flat-bottomed circular sitz-bath. The current flows outwards in all directions with diminishing velocity, and the water, resurging from the circumference, makes a breaking wave with a circular front facing the centre of the bath. As the depth of water behind the wave increases the velocity of the wave also increases, so that its front closes in towards the centre where the outflowing current is more rapid. The circle is presently reduced, at first slowly, afterwards more rapidly, so that only a small hole is left, and finally the wave closes in completely upon the down-pouring column of water.

surface. A mound of water forms in the neighbourhood of the obstruction (its precise position relatively thereto depending upon the circumstances of depth and speed), and a hollow and a second crest, and then a third, a fourth, and so on, appear farther down-stream, a train of waves speedily being formed. If the obstruction be now dragged up-stream, the whole train of waves moves up-stream with it, preserving their position relatively to one another (which is the second connotion of the epithet " stationary " as applied to them). In performing this simple experiment the close resemblance between the ordinary waves of rivers and ship-waves becomes at once apparent. The analogy is yet further brought home when one notices the waves formed by a model or toy vessel moored in a rapid stream. The familiar train of waves shown by a ship steaming through still water is here reproduced in the water which flows past the stationary vessel.

There are, however, considerable differences in the appearances usually presented by ship-waves and river-waves, which are due partly to the fact that the latter are produced by disturbances which affect the water throughout its whole depth, and the former are generally only superficial. Again, river-waves, when caused by a weir, extend in straight parallel ridges at right angles to the current, quite across the stream, a form very different from the wave-track of a ship.

A solitary boulder in mid-stream does, however, reproduce, very roughly, the wave-track of a ship, a series of waves being formed on either side, each wave inclined at an angle which appears to be about the same as in the case of ship-waves, viz., $19\frac{1}{2}°$ to the current, each succeeding wave projecting somewhat farther into the stream than its predecessor. There is generally but little indication visible of any system of transverse waves like the thwart-ship waves which are comprised between the diverging, or "échelon," waves of a ship's track.

When river-waves arise from the retardation caused by a rough bank, or where a stream narrows, or where it enters upon a different gradient, the wave-front is inclined to the bank. If the stream be wide, the oblique standing waves are of greater elevation near the bank, the height diminishing farther out, the centre of the river being smooth. If, however, the stream be narrow, the standing waves originating from the opposite banks are superposed in the centre of the stream, and the combined crests there have a greater amplitude than either separately. Thus the highest wave

STATIONARY WAVES CAUSED BY A WEIR ON THE RIVER AARE, SWITZERLAND.

is in this case found in the centre of the stream, as may be seen, for example, near the spot, called Bloody Run, opposite Foster's Flats, in the rapids between Niagara Whirlpool and Lewiston.

In 1896 I noticed some facts relating to waves in rivers of which I found no published explanation. The first was that the water of rivers, perticularly rapid mountain streams—*e.g.*, at Meran, in the Tyrol—does not maintain a constant level at any fixed spot, but, on the contrary, oscillates perceptibly with a motion sufficiently rapid and short in period to be readily perceived by the eye. This indicated that there was something of the character of a progressive wave, but I could not at that time see any travelling wave.

The second observation was that the so-called stationary waves (*e.g.*, on the Eisah, above Botzen, and at the Bingen Rapids, on the Rhine) were not perfectly stationary, but oscillated somewhat about a mean position. Their most noticeable movement was that, from time to time, they charged somewhat rapidly a foot or two up-stream; and in this case the cusped waves broke as waves break on a sea-beach. It appeared to me that the second phenomenon was related to the first in the following way: granting that the "stationary" waves are travelling up-stream as fast as the current flows, then if the speed of the current be suddenly diminished, the speed of the waves will be too great, and they will charge up-stream. Thus, if the current be subject to fluctuation, as the first observation seemed to indicate, we should expect the " standing " waves to fluctuate about a mean position.

A third fact, also, best observed in mountain streams—*e.g.*, the Lutschine, at Grindelwald, in Switzerland—was that in the shallows of little bays there was always a succession of progressive waves rushing towards the shore, as waves come in on a sloping sea-beach. These " rollers " in the little bays were evidently connected with the oscillation or throbbing of the stream. A long series of these " rollers " was timed just below Speybridge, near Grantown, N.B., when the " Galloping Spey " was swollen by melting snow and ice, in February, 1900. They were only roughly periodic. They rolled in upon the shore in a direction about at right angles to the current—their direction being, of course, conditioned by the shallowing of the water ; and it was of interest to observe that these waves rippled the sand at right angles to their motion, although the current drifted the sand-grains parallel to the ripple ridges.

Beyond the frequent repetition of these three observations in different rivers, I was not able to progress in this matter for some time. I determined, however, to see what I could learn of wave phenomena in rivers, particularly those connected with the pulsation or throbbing which I had noticed, by a visit to the River Niagara, where I thought I could see such things in their full and free development.

Cross-stream Progressive Waves. Observations in Niagara River

I arrived at Niagara Falls, N.Y., on July 8, 1903, accompanied by my wife, who has shared in all my travels in search of wave phenomena. The next three weeks were spent in observation between Niagara Falls and Lewiston, after which a voyage was made from Kingston, Ontario, to Montreal, passing through numerous falls and rapids on the St. Lawrence.

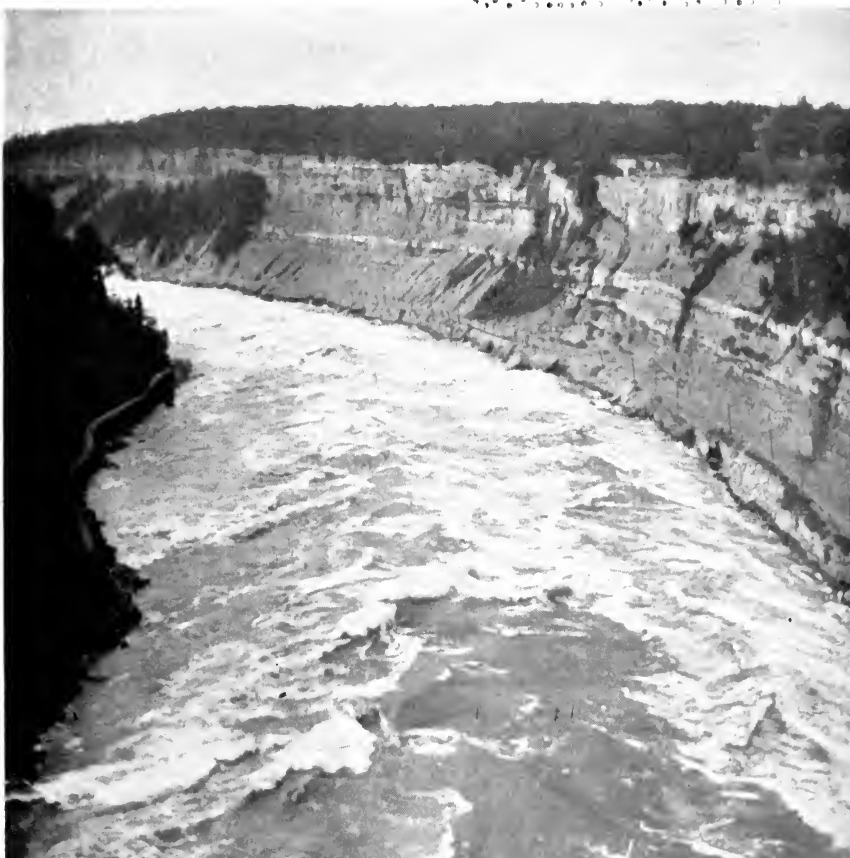
Above the Falls of Niagara the river is wide and generally shallow, flowing very swiftly on a considerable gradient over an uneven, rocky bottom. Between the American shore and Goat Island the water is shallowest. Above the bridge connecting them I was able to see waves progressing downstream which I thought "faced"—*i.e.*, had their steeper face—turned down-stream and towards the shore, instead of up-stream and away from the shore, as the stationary waves are. The travelling waves were not conspicuous, however, and I was not able to detect similar ones (facing down-stream) in the deep waters of the Whirlpool Rapids.

In the upper rapids of Niagara regular trains of waves are not prominent. The most noticeable waves are such as that beyond the last "Sister Island," where a huge mass of water surmounts a rocky protuberance, to leeward of which the water curls back in a fine cusp.

In a little sheltered channel among the islands, where the water flowed less tumultuously, much better examples could be seen of a regular train of waves. From Lunar Island I saw one of the cusped waves near the brink of the American Falls break periodically, thus :

In 57 seconds the wave broke 7 times ;
" 62 " " " " 8 "

corresponding to periods of 8.14 and 7.77 seconds respectively. This is in the same part of the river where I observed the progressive waves. I postpone until another section the account of certain phenomena of the actual falls, and, passing by without remark the 2-mile stretch of deep water



BIRD'S-EYE VIEW OF WAVES IN WHIRLPOOL RAPIDS, NIAGARA.

(160 feet to 190 feet), with scarcely any fall of level, which succeeds them, I come to the second rapids of the Niagara River, called the Whirlpool Rapids, from the pool at their lower end. The fall is 50 feet per mile, nearly 1 in 100. The width of the Rapids is only about 350 feet, the depth is stated to be 35 feet to 50 feet, and the reputed velocity is 30 miles per hour.[1] The course of the river here is curved, the apex of the curve being approximately at the "Whirlpool Rapids" station of the Niagara Gorge Light Railway, situated on the right bank. A very fine general view of these rapids is obtained from the footpath of the high level railway bridge at their upper end, and an excellent view of the waves near the railway station is obtained from the cliffs of the left bank opposite thereto. Waves commence a little above the bridge, where the gradient of the bottom increases and the water begins to flow more swiftly. There are two sets of waves originating from the right and left bank respectively. The first few waves are smoothly rounded in form and practically steady in position. Lower down, where sets of waves originating from the opposite banks extend sufficiently far out to meet each other, they are

[1] G. K. Gilbert: "Explanation of United States Geological Survey Map of Niagara River."

often cusped and foaming, and they shift somewhat rapidly for a short distance up and down about a mean position.

Numerous standing waves originate from successive positions on the banks, the position being determined doubtless by changes of pressure and, consequently, of velocity. Such change of pressure and velocity is obviously produced in some places by rocky obstructions, but in some instances, particularly opposite the railway station, the change of direction of the current probably contributes to the effect. No long and regular trains of waves can be observed, except just at the commencement, but the positions of the principal mounds of water are perfectly definite, so that (as long as the river remains at a certain level) these waves are recognisable individuals. Nevertheless, I noticed from my elevated stations on the bridge and the cliffs that in this terrible rapid (where the combined depth, speed, and volume are so unusually great) the throbbing, which is so slight a feature in most wavy streams, had developed to a remarkable extent. The stationary waves of the river differed from those of quieter streams in the same way that the bow-wave of a steamer in a heavy sea differs from the bow-wave in smooth water. In the latter the bow-

LEAPING WAVE, WHIRLPOOL RAPIDS, NIAGARA.

wave is constant in size and steady in position, but in a heavy sea the vessel throws off from her bows a succession of waves. Similarly, I saw the standing waves near each shore periodically wax and wane (though never waning to less than, say, three-fourths of their maximum), and as each passed its maximum it disengaged a conspicuous and considerable travelling wave, which surged forward (facing diagonally up-stream) towards the centre of the stream. The waves travelling outwards from each bank met in the middle of the stream with much commotion and throwing up of spray, after which they could be clearly seen to have passed right through each other, and to continue each its course towards the opposite shore. The wave, however, is drifting down-stream all the time; the resulting motion of the mound of foaming water being more down-stream than across stream, for the current velocity is greater than the wave velocity relatively to the bank.

Viewed from the edge of the torrent at Whirlpool Rapids Station, the great standing mounds of water in the centre of the stream towered up above the line of sight. They are formed (as I knew from my bird's-eye reconnaissance) where the standing waves, diverging from the banks, cross one another. They fluctuated continually in height (from 15 feet to 20 feet I estimated)[1] and also in position, but the amount of shifting was not great —perhaps one-half of the length of the mound of water. This staggering and heaving conveys the notion of efforts so great that some breakdown must soon occur. And while I watched enthralled the breathless heavings of the standing waves, a surge came rushing upon the shore where I stood, as if the river would suddenly rise and overwhelm me. I drew back, realising that my post of observation was unsafe. Acting on the ordinary experience of rivers as flowing with practically steady motion, I had not sufficiently allowed for the amount of throbbing in the Niagara Rapids. Of course, the rush of water which drove me back was not the commencement of a continuous rise, but merely the discharge of a wave, and the water receded again with a somewhat more deliberate motion, only to make way for another dashing surge. The surge was timed by the covering and exposure of a rock:

Number of Times Rock Covered.

First Minute.	Second Minute.	Third Minute.	Fourth Minute.	Fifth Minute.
3	5	4	4	5

Average period, 14·3 seconds.

[1] The late Mr. T. V. Welch, formerly Superintendent of the New York State Reservation at Niagara, informed me that they are estimated at 30 feet when at their highest.

Such a surge is well shown in cinematograph views of the Rapids. The vertical rise and fall of this surge upon the shore was about 2 feet. It is easy to realise that it is connected with the sway and heave of the standing waves, and recollecting what I had seen from above, I naturally connected it with the travelling waves which come from near the opposite shore.

My feeling that the standing waves were heaving and swaying too much for permanence was presently justified. After watching for a time the seething and roaring waters, the great billow before me suddenly leaped into the air, scattering its waters in showers of spray, which fell to leeward upon the river with a "swish," whilst a much diminished mound was seen where the explosion occurred. It was, however, only a matter of seconds for the standing wave to grow again to its normal dimensions. I have called this phenomenon the "leaping wave." Doubtless it may be seen in many places on Niagara, and in other such tumultuous waters, but the best place, as far as I know, for observing the phenomenon is at the Whirlpool Rapids Station. Presumably, the spot for the station was selected on account of its being opposite the place of greatest turbulence.

I was, fortunately, able by actual observation to trace the phenomenon to its cause ; for, returning to the cliffs on the Canadian side directly above the spot, I saw travelling waves buffeting their way to mid-stream from either side (but swept down-stream, so that their resulting course was inclined at an acute angle with the current) meet together just where the crossing of the standing waves made one of the great mounds of water opposite the railway station. When the two travelling waves met each other and the great standing wave, the water leaped high into the air, shattering and scattering all regularity of form or structure. After seeing the thing from this point of vantage, I was able on another occasion to recognise the process from the nearer but lower point of view close to the railway station. My eye having become accustomed to the maze of motion (acquiring thus a temporary efficiency far beyond one's ordinary powers of seeing), I actually saw several waves converge at the same time to produce a leaping wave.

I may add that I never noticed any great leaping up of the water except the leaping of a standing wave when progressive waves converged upon it.

In the voyage from Kingston, Ontario, to Montreal, passing through many rapids, including those of Lachine, I was able to make my observations under another set of conditions—viz., while

WAVES IN WHIRLPOOL RAPIDS, NIAGARA.

sharing the motion of the current, so that the only movement of the water which the eye had to follow was its periodic or wave motion. The changed conditions of vision are well indicated by the photographs then taken, in which there is no indication of the shutter being too slow, for the particles of foam, &c., travelled along at the same speed as the camera. As we passed through one after another of the St. Lawrence rapids, I noticed repeatedly that the first few waves were rounded in form, unbroken in surface, constant in size, and practically fixed in position. Lower down, however, where two or more trains of waves intersected one another, they became cusped and foaming, breaking also and sometimes fluctuating.

Some part of this difference may be due to increased speed in the lower part of the rapid, but it was fairly evident that the changed character of the waves was mainly due to superposition.

The most conspicuous billows, or apparent waves, in torrents are usually of small lateral extension, for they are produced where two standing waves cross, and each standing wave is usually inclined at about 20° to the direction of the current. In the Niagara Rapids below the Whirlpool, opposite Foster's Flats (Devil's Hole Station), there is a splendid series of such combination standing waves. The course of the river being here straight, there is less irregularity than at the bend of the Whirlpool Rapids. The distance from crest to crest in the direction of the current was 100 feet, but this is not a true "wave-length" in the physical sense.

It is now incumbent to explain the co-existence of the ordinary diagonal standing waves of rivers with travelling waves facing diagonally up-stream in the rapids of Niagara and the St. Lawrence.

The absolute steadiness of standing waves can only be secured by absolute steadiness of current. In a river with a rough bed and a crooked course it is impossible that the motion should be perfectly steady if the current be even moderately swift, for (to take the principal and most evident cause of fluctuation) eddies are alternately formed and released. By this means a standing wave is caused to fluctuate as the "unwinding scrolls" and other irregularities follow one another down the stream. Generally speaking, the fluctuations so produced in a wave near the right bank will not synchronise with those of a wave near the left bank, for such irregularities of flow of the river are generally partial, not affecting simultaneously the whole cross-section of the stream.

Wave-motion is essentially differential, and if the rate of change of motion be slow, the effect

WAVES IN A RAPID ON THE ST. LAWRENCE, TAKEN GOING DOWN-STREAM IN A STEAMER.

on a wave is slight. Thus, such fluctuations of current generally only produce a flicker in the stationary waves, as described in the earliest observations recorded above. But if wave be superimposed upon wave, the effect of such fluctuation is intensified in a very high ratio. The combination wave may be regarded as a " higher power " of the original quantity, and the effect of an inequality of current as affecting the fluctuation of the combined system will increase in a rapid ratio. The fluctuation of a waved wave (as I may term it) is much more sharp and sudden than that of a simple wave. The effect will also be more marked when the standing waves are themselves steep and high relatively to their wave-length.

Thus the fluctuation of the standing waves of the Whirlpool Rapids becomes sufficiently great for the disengagement of visible travelling waves. The independence of various causes of unequal flow in different parts of the stream makes the travelling waves arise independently in different places, and their synchronisms are, therefore, irregularly timed. Great leaping waves are only caused when a number of them (in their resultant drift) converge simultaneously upon a combination standing wave.

These cross-stream progressive waves do not, however, exhaust the possibilities of progressive waves in rivers, and I was on the look-out more particularly for waves facing down-stream and progressing through the water in a down-stream direction. Such waves would, of course, pass the bank more rapidly than the water itself, for their apparent velocity would be that of the current *plus* the proper motion of the wave.

Near Devil's Hole Station, opposite to Foster's Flats, on the rapids below the Whirlpool, I observed that from time to time freshets came down the river, raising the level of the water on the bank for as much as 90 seconds. Thus at 11 hours 26 minutes 5 seconds a large freshet arrived, raising the general level of the water about 12 inches. Duration of high water, 1½ minutes.

11 hours 32 minutes 5 seconds, another freshet; high water, 1½ minutes.

11 hours 37 minutes 5 seconds, a small freshet.

11 hours 42 minutes 5 seconds, a small freshet.

I could not, however, perceive any visible travelling wave, nor was there anything to indicate that these freshets travelled faster than the current. If they had been due to "long waves" progressing in the direction of the stream, they would have been travelling at some much greater velocity, perhaps twice as fast, for the depth here is very considerable. I am inclined to think, therefore, that this kind of swelling of the river, which co-existed with the shorter period waves which were coming in on the shore all the time, is due to the intermittent disengagement of masses of swirling water from the great whirlpool up above. Some confirmation of this view is afforded—first, by watching the up-wellings which take place in the whirlpool near the exit, and also by the appearances of such masses of swirling water lower down the Foster's Flats Rapids, where there are fewer standing waves. It is not uncommon here to see a cyclone and an anticyclone of water drifting down-stream side by side with a difference of level (reckoned from the crown of the anticyclone to the pit of the cyclone) of probably 5 feet or 6 feet. In these there is horizontal circulation of water about vertical axes.

Thus in the deeper waters of Niagara I never saw any repetition of down-stream progressive waves such as I believed I had detected in the shallow water above the American Falls. This might be explained either by their non-existence or by their being too flat to be visible in deep water.

In the next chapter I shall give an account of the circumstances under which a stream of water flows in a series of down-stream bores.

CHAPTER XI

On streams which flow as a series of roll-waves—Observations on a conduit from Territet to Glion—Observations on the conduit of the Grünnbach (Merlingen, Thunersee)—Observations on the conduit of the Guntenbach (Gunten, Thunersee).

On Streams which flow as a Series of Roll-waves

ON June 11, 1904, I walked from Grindelwald to view the Apbach Waterfall. Alongside the sheet of water which leaped from the overhanging part of the rock was a small body of water sliding down the precipitous, but not vertical, part of the rock. The water here would have been only a small fraction of an inch in depth if it had been uniformly spread, but it was, on the contrary, flowing in detached portions, having the form of small, wedge-shaped, progressive "solitary" waves, miniature bores, about $\frac{1}{8}$ inch in amplitude, separated by portions of rock which were covered by a film of merely capillary thickness.

The same phenomenon was seen on another occasion, on a slightly larger scale, where the water of the little Pfanenbach flows down a precipitous rock-face near Gunten, on the Thunersee. Here, again, the runnels of water were not wide, and the wave-front of the progressive waves was V-shaped.

Water flowing in a broad, thin sheet upon a sloping platform goes in progressive wavelets, which have a widely extended wave-front, presenting a series of parallel ridges, which recall the typical form of surface waves more forcibly than the V-shaped wavelets of a film flowing in a narrow runnel. I have detected the progressive-wavelet form of flow on the face of a vertical slab of smooth stone down which water flowed, but have seen it better upon the sloping, polished marble slab of a fishmonger's shop when being washed down with water flowing from a pipe. The outflow from the pipe may not have been absolutely steady; but any unsteadiness there may have been was certainly slight, whereas the flow of the sheet of water rapidly formed itself into a procession of progressive wavelets, which were both conspicuous and regular. The ridges were about 9 inches apart. The same thing can be seen where the street pavement or a ship's deck is flushed from a large hose.

Observations on a Conduit from Territet to Glion

From Territet (on the Lake of Geneva) to Glion, about 800 feet above, there runs a funicular railway, with an average ascent of nearly 1 in 2. On the east of the line is a cement conduit, 14 inches wide, with flat bottom and nearly vertical sides, which carries off small quantities of water overflowing from the machinery, as well as, perhaps, a little drainage water. The regularity of the conduit is interrupted above the bridge which crosses it on a level with the Church of Les Planches, and the water there flows in the ordinary manner. It is only from the place where the cement floor commences that the waves become noticeable. The slight, rapid, and confused inequalities of the flickering flow here become regularised into transverse progressive waves in the course of a few yards, and these waves dash past the bridge and go foaming on as far as the railway station in an orderly and regular procession, dozens of frothy crests being simultaneously visible.

On February 9, 1905, I measured the depth at the crests of the waves and found it to be 0.2 inches, and at the troughs 0.1 inch. The apparent period (that is to say, the interval of time separating the passage of two succeeding crests past the observer on the bank) was 0.4 second on one occasion and 0.7 second on another. The wave-length attains a maximum of about 18 inches or 2 feet before the end of the run is nearly reached. The reason why the waves soon attain a uniform maximum size is that the increase of depth at the crests is accompanied by a corresponding diminution of depth at the troughs where the water becomes too far reduced for further growth. On one occasion I have seen the sudden accession of a little more water (from the passing train) greatly increase the size of the waves. On another occasion, however, near the Glion Station, when much water was poured into the conduit at the end of the journey, the progressive waves vanished altogether. There appeared instead diagonal stationary waves, originating from both sides of the conduit. When the excess of water ran off, the shallower stream ceased to be steady, and again ran in a series of progressive waves.

The cement floor and sides of the conduit are not, of course, nearly so smooth as the polished marble slab above referred to, but their surface is plain, uniform, and free from palpable excrescences. The course is straight, and of uniform gradient for considerable distances. The steepness of the gradient is immensely greater than in rivers.

The wave phenomena in the conduit are absolutely different from those normal to rapid rivers of considerable depth. In the latter, any cause which retards the flow gives rise to waves stationary as regards the bank, with their steeper face upstream, and travelling through the water in a direction more or less directly up-stream. In the conduit, on the contrary, the waves, which have their steep face down-stream, travel through the water down-stream, as I proved by measurements, to be quoted later. In rivers of moderate depths where standing waves arise, the dominant factor in wave-making is pressure, the effects of friction being relatively very small. Thus, where pressure is increased, the stream-lines open out and the level of the surface rises, in the manner and for the reasons which have been set forth by many authors who have dealt with the theory of ship-waves.

The total depth is greater at the crest of the waves, and here the flow is slower; less at the troughs where the flow is quicker; and a state of continuous flow is thus maintained, an equal quantity of water passing each cross-section of the river in each unit of time.

But in the conduit, where the depth is initially very small, the frictional resistance of the bed becomes the dominant factor in determining the rate of flow. If this small depth be increased, the rate of flow is at once greatly accelerated, for the upper layers flow with considerable freedom upon a couch of water, whereas the lowest layer clings to the bed. Thus a momentary retardation of flow at any spot, by increasing the depth there, enables the water which then arrives to flow with much greater speed. The excrescence caused by any momentary check therefore dashes down-stream. Thus every retardation quickly causes acceleration. This condition necessitates the substitution of a gushing for a continuous flow. The more highly developed are the down-stream progressive waves, or roll-waves, the more gushy is the stream.

I shall now give some account of observations of these spontaneous roll-waves in shallow streams (generally artificial conduits) which I made in Switzerland during 1904 and 1905. The waves in the conduits, which are much easier to observe than the corresponding waves in natural channels, throw some light upon occurrences which are confused and obscured under natural conditions.

When looking at water flowing past in a shallow channel, I find that the eye is generally fixed by stationary features of the surface, such as diagonal standing waves originating from the banks. When the gaze is thus fixed, the surface of the flowing water has either a smoothed-out appearance or that of stationary streaks or stripes. If, however, the eye can be trained to follow the water in its flow, it will be seen that its surface is usually covered with travelling inequalities. This habit of vision is somewhat difficult to acquire, and the movement of the eye is always liable to be arrested involuntarily by some fixed object. If, however, a small dead leaf, or a short piece of straw, or some such light thing, be cast upon the stream, the eye follows it in its drift naturally and with ease; and then, in shallow channels with a steep gradient, the surface of the water, instead of having a smoothed-out or striped look, is found to be covered with rounded excrescences travelling at about the speed of the stream. The smoothed surface is, in fact, an optical illusion. An excellent opportunity of following up this observation was afforded me by journeying up and down on the funicular cars from Territet to Glion, and from Vevey to Mont Pélerin. The appearance of the water when coming down (the car sometimes travelling at almost exactly the speed of the current) was very different from that when going up, or when standing on the banks. On the Mont Pélerin funicular, when going up, the only surface inequalities visible were diagonal standing waves. Coming down, a knobbly surface travelled along with us, one of the knobs of water occasionally bursting. There were no regular roll-waves in this case, but in that of the Territet-Glion conduit I was able from the car, which travelled down at nearly the same speed as the roll-waves, to observe that, in addition to the larger waves with front extending the whole breadth of the stream, there were innumerable embryo waves, which seemed to be in continual course of production. How embryo waves become united into relatively large roll-waves, regular in form and travelling in orderly procession, can be better explained from the phenomena observed in the conduit of the Grünnbach, at Merlingen, on the Thunersee, Switzerland, during 1904 and 1905.

Observations on the Conduit of the Grünnbach (Merlingen, Thunersee)

The Grünnbach is the torrent flowing through the great gorge of the Justisthal to the Thunersee. The lower portions are first controlled by a series of weirs causing waterfalls, and, finally, for the last 1,360 feet, the stream is carried in a straight, paved conduit about 7 feet deep and 15 feet wide, with nearly vertical sides, the form and structure being shown on the Plate. The lip of the conduit is several feet above the highest level of the lake, and the water leaps the outflow as a waterfall. The object of a structure so considerable as this conduit is, not the accommodation of the usual flow of water, but the provision for the great rush which takes place when a thunderstorm bursts over the Justisthal, especially in springtime before the snows are melted. Under ordinary conditions, even in wet weather, the average depth of water in the conduit is seldom more than 3 inches. The speed is so great, however, on a slope nowhere less than 1 in 14, that the discharge is not insignificant. With a depth of about 2 inches, the speed is about 10 feet per second; but if the depth were increased to 3 feet or 4 feet, the speed would, no doubt, be very much greater.

The last of the series of waterfalls above the conduit discharges the stream into a pool, whence it flows over a piece of slightly hollowed pavement for 51 feet, when it enters the rectangular channel. The discharge of the upper waterfall is steady, in the sense that there is no cadence, the minor flickerings of one part neutralising those of another. The pool is of irregular depth, and the discharge from it has no regular pulsation. Nevertheless, as the water rushes over the slightly

ROLL-WAVES IN THE GRÜNNBACH CONDUIT, LOOKING UP-STREAM.

hollowed piece of pavement, it can be seen to flow gushingly, for the greater regularity of cross-section to some extent co-ordinates the flickerings, and the smaller depth tends to increase the gushiness of flow, as has already been explained.

At the entrance to, and for the first few yards of, the rectangular, flat-bottomed, paved channel these embryo roll-waves pass the eye in too rapid succession to be accurately counted, but there are about 120 per minute. They are here little more than ripples, and the fronts, which face down-stream, are free from white froth. As we walk down the bank of the conduit, we observe that a regularising process is at work, which, in a short distance, produces from this hurried and confused crowd of progressive wavelets an ordered series of roll-waves of greater amplitude, with foaming fronts facing down-stream, extending across the channel in a straight line at right angles to its axis. On June 6, 1904, at 465 feet from the entrance to the paved channel, there were notable larger waves; but there were many minor ones also, and the appearance was still somewhat confused. At a distance of 567 feet from the entrance to the paved channel there was no more confusion, a distinct series of waves, 33 per minute, passing the observer; whilst after travelling another 554 feet (or 1,121 feet in all), there were 20 waves passing every second; the height and length of the waves having increased proportionately, and the depths at the troughs being correspondingly diminished. The current is much accelerated at and near the crests, and considerably diminished in speed at the troughs, as is readily seen by watching the progress of small floating bodies.

At the outfall into the lake, a further distance of 240 feet, or 1,361 feet in all, the waves were 17 per minute. The outfall of water is often twice or three times as great when a roll-wave crest arrives as at other times. The fall of the roll-wave is accompanied by a booming noise, and the flash of the outflowing water is sometimes visible at a distance of 2 miles.

On September 16, 1904, with a uniform depth in the upper part of the channel of 3 inches to $3\frac{1}{2}$ inches, as nearly as could be determined, the water at the outflow had a depth of 8 inches at the crests and $1\frac{1}{2}$ inches at the troughs of the waves. The time of flow of the water from entrance to exit of the paved channel was 90.2 seconds—a short time indeed for the evolution of such a cadence from a mere flicker, and for the development of a wave amplitude from, say, $\frac{1}{20}$ inch to at least 6

ROLL-WAVE LEAPING THE OUTFALL OF THE GRÜNNBACH CONDUIT.

inches. The distance between the wave-crests in the lower part of the channel was on this day 66 feet.

The process of growth is easily observed, the larger wave-crests catching up the smaller and incorporating them, the wave-velocity being greater where the depth is greatest. As soon as the difference of depth between troughs and crests of the larger waves becomes considerable, the process of incorporation of the smaller wave-crests is much hastened; for when they are situated in the troughs of the larger waves their total speed is much diminished.

On several days the speed of the current and the rate at which the waves travelled past the observer were determined. The latter, which may be called the apparent speed of the waves, is the velocity of the current plus the rate at which the wave travels through the water in a downstream direction. Deducting the velocity of the current from the apparent velocity of the wave, we obtain the true velocity of the wave. If this should be found to be nearly the same as the calculated velocity of a long wave (viz., $V = \sqrt{g h}$, where V = velocity, g = acceleration of gravity, and h = depth, all expressed in feet and seconds), it may be safely concluded that these roll-waves progress by gravitational transmission of pressure in the manner postulated in the theory of long waves. The conditions are so different from those usually contemplated for long waves that such a test is far from superfluous.

True Velocity of Roll-Waves in the Grünnbach Conduit.

Date.	Observed Depth at Crest.	Observed Depth at Trough.	Observed Speed (F.P.S.).	Calculated Speed (F.P.S.).
Aug. 26, 1904 ...	2·5 in.	1 in.	2·06	2·58
Sept. 8, 1904 ...	4·0 "	1 "	3·275	3·27
June 15, 1905 ...	4·5 "	2 "	3·54	3·47

There was, however, one observation which did not agree with the theoretical numbers, and was also out of accord with the other three observations, viz.:

Date.	Observed Depth at Crest.	Observed Depth at Trough.	Observed Speed (F.P.S.).	Calculated Speed (F.P.S.).
Sept. 16, 1904 ...	8 in.	1·5 in.	3	4·60

Or, putting it the other way, the calculated depth at crest for the observed speed is only 4.6 inches, the difference from the observed depth of 8 inches being too great for error of observation. This was the occasion of greatest observed wave development on the Grünnbach, the depth of 1.5 inches at trough being certainly small for the transmission of a wave with an amplitude from trough to crest of 6.5 inches. I think the discrepancy, however, is to be explained not so much by this circumstance as by an error introduced by the determination of the velocity of the current. I made a note at the time that the floating objects which I was observing were several times caught and pushed along by the foaming front of the waves. Thus their speed was probably greater than the average velocity of the current, making the wave-velocity come out too low.

On some occasions the failure of the stream just before the arrival of the crest was distinctly noticeable—a fact in itself, and apart from the measurements, indicating that the waves differ more in appearance than in essence from ordinary waves. The waves had not completed their growth when they reached the outflow; but if the length of the conduit could be much increased, we should doubtless see the last part of the course traversed by a series of waves of uniform height, length, and speed, as occurred after a short run in the shallower, but smoother, conduit of the Territet-Glion Funicular Railway.

The following table shows the number of wave-crests passing per minute at different distances from the entrance of the channel, taken on several days,

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with the depth of water in the upper portion of the channel varying from 1.5 inches to 3 inches or 3.5 inches.

Date.	Distance in Feet from Origin.	Period in Seconds.	Distance ÷ Period.	Ratio of Period to that at Outfall.
June 24, 1904	465	2·14	217·3	0·458
"	567	—	—	—
"	1121	4·00	280·2	0·856
"	1361	4·67	291·4	1·000
June 25, 1904	465	—	—	—
"	567	2·00	283·5	0·467
"	1121	3·16	354·7	0·737
"	1361	4·29	317·2	1·000
June 26, 1904	465	—	—	—
"	567	1·82	311·5	0·513
"	1121	3·00	373·7	0·851
"	1361	3·53	385·6	1·000
June 28, 1904	465	1·97	236·0	0·414
"	567	—	—	—
"	1121	—	—	—
"	1361	4·76	285·9	1·000
Sept. 16, 1904	465	1·50	310·0	0·411
"	567	—	—	—
"	1121	—	—	—
"	1361	3·65	370·0	1·000

The period on any one occasion—*i.e.*, for a particular depth of water—is proportional to the wave-length. If the wave-lengths were proportional to the distance run, for a particular depth of water, then the distance run divided by the period in seconds would be a constant quantity.

for any one day. The figures show a less simple relationship, the period increasing somewhat slowly at first, although towards the end of the course the increase is more nearly proportional to distance run.

It will be seen from the tables that the rate of increase of period is nearly the same on different days when the depths differed by moderate amounts. In order to make a thoroughly satisfactory examination of such relationship it would be necessary to know, not only the distance run by the wave relatively to the bank, but also the distance travelled through the water, which was not determined on every occasion.

The following figures show the degree of irregularity in the intervals between successive wave-crests at the outfall. This measurement, made with a stop-watch, is very easily taken, and is free from the uncertainties which attended the measurement of depth, and, to some extent, of the velocity of current.

The intervals between Successive Wave-crests at Outfall of the Grünnbach. In Seconds.

5,	3,	4,	8,	4,	7,	4,	4,	2,	1,
5,	4,	5,	6,	4,	5,	3,	3,	4,	1,
6,	3,	4,	2,	4,	4,	3,	1,	7,	2,
7,	9,	2,	9,	8,	1,	10,	1,	5,	6,
1,	4,	9,	1,	6,	1,	2,	6,	7,	4,

6	waves had a period of			1	second
6	"	"	"	2	seconds
5	"	"	"	3	"
14	"	"	"	4	"
6	"	"	"	5	"
5	"	"	"	6	"
4	"	"	"	7	"
2	"	"	"	8	"
3	"	"	"	9	"
1	wave	"	"	10	"

Reverting from figures to the description of appearance, I may note the following additional circumstances observed in the Grünnbach conduit, which tend to elucidate the origin and mode of growth of the train, or series, of roll-waves.

The first noticeable agency of growth is the catching up of the smaller waves by the larger, due to more rapid motion of the latter; but a new factor (not possible on the cement floor of the Glion conduit) is the increase of amplitude as the front passes over each transverse ridge of the flag pavement. It appears, therefore, that we have here a case of a progressive wave increased, not merely by friction with a flat bed, but also by passing over perceptible transverse inequalities. The depths being small, the reasoning previously employed to explain discontinuous flow as resulting from local increase of depth still holds good.

ROLL-WAVES IN THE GRÜNNBACH CONDUIT, LOOKING DOWN-STREAM.

There is one portion of the conduit paved more smoothly, in larger and better trimmed blocks, than the rest. Here, when there was little water, the wave development proceeded best; afterwards, on entering the rougher part, the wave was somewhat broken up. But when the depth of water was greater, there was but little growth of the wave in passing over the smoother pavement, the growth becoming more rapid when the wave began to ride over the transverse joints of the rougher pavement. Thus, for the best development of the wave, there should exist a certain proportionality between the amplitude of the transverse corrugation and the depth of the water.

The longitudinal joints of the pavement tended somewhat to destroy the transverse wave, especially when any irregularity of channel caused the wave to pass somewhat obliquely across them.

There was a good deal of lateral wave motion, which sent a considerable wash against the sides of the channel; but these, being nearly vertical, reflected the wave back again, and thus tended to keep the front transversal. About half-way down the conduit the slope is somewhat abruptly diminished, remaining thereafter less than in the upper half. It was always a matter of surprise to me that no obvious change in the waves occurred when the gradient diminished.

The uniformity of depth in this conduit is, of course, a most important factor in preserving the transverse waves, and the unequal depth (in cross-section) in natural streams equally tends to prevent their development. I saw an excellent example of this at St. Maurice, in the Rhône Valley, where a paved conduit terminated in a channel encumbered by gravel, through which the stream had made for itself the usual winding course, with unequal depths on the two sides. The conduit delivered strong transverse roll-waves at intervals of a few seconds, each of which vanished almost instantaneously upon entering the winding channel of unequal depths in cross-section.

Since the velocity of the wave relatively to the banks is that of the current plus the true wave-velocity, and the latter is greater for deep water, it follows that the wave-front loses its transversality when the cross-section of the stream is not uniform, and this is more marked in down-stream roll-waves than in up-stream bores (where current and wave oppose one another). This is one reason why down-stream progressive waves are so much less familiar than up-stream bores.

Observation of Roll-waves in the Conduit of the Guntenbach, Gunten, Thunersee, Switzerland

The Guntenbach, which drains a smaller valley than the Grünnbach, runs for the last 1,000 feet of its course in a paved conduit, with a practically uniform gradient of 1 in 22, as measured with a small Abney level. The sides of this conduit are sloping, not vertical, as in the Grünnbach; the paving-stones are more irregular in form, and the depressions at their joints are deeper, as well as less regular. No roll-waves were ever seen in the upper part of the conduit;[1] they originated suddenly lower down, generally at or below the lowest bridge, which was 370 feet from the outfall. Thus the course of events differed considerably from that in the Grünnbach, where the waves could be watched through all their stages of development. On the roughly-paved Guntenbach it took much watching to discover the origin of the roll-waves. I would stand near by where they generally commenced, watching the water closely; then, to the right or to left of where I was looking, I would hear a sudden sound like that of the word "flop," and,

[1] The upper part of the conduit has in many places deep longitudinal grooves in the central paving-stones. The cross-section of the lower part is more nearly uniform.

on turning quickly, there would be a fully-formed roll-wave extending transversely across the whole channel. Once formed, they were never subsequently dissipated, but, on the contrary, grew quickly as they travelled through the water. The reason for their growth was not evident from mere observation. The outfall into the lake was in fairly regular cadence, the phenomenon being similar to that of the Grünnbach, though not so crisp. This want of crispness was evidently due partly to the sloping sides, which did not keep the wave-front so perfectly transverse as the Grünnbach. The Plate is from photographs taken at intervals of a few seconds, the first photograph showing the outfall of the Guntenbach at a wave-trough, the second at a wave-crest.

After watching for three months, I came to the conclusion that the mode of origin of the waves in the Guntenbach was entirely different from that in the Grünnbach. In the former there were some slight, long depressions extending the whole width of the pavement which were almost masked by its general roughness. The most marked depression was under the lowest bridge, and somewhat concealed thereby. I found that the roll-wave started here more often than at any other point, and I noticed that up-standing edges of the pavement

OUTFALL OF THE GUNTENBACH AT THE WAVE-TROUGH, AND (A FEW SECONDS LATER) AT THE WAVE-CREST.

stones made something resembling a dam at the lower end of what was, in fact, a pool. Here the wave seemed to originate by the sudden emptying of the pool. The depth being very small (generally not more than $1\frac{1}{2}$ inches or 2 inches on the sill), and the pool being several yards long, there was great sensitiveness to the slight flicker always perceptible in this and similar streams. Wherever in the course of these irregular flickerings a slight deficiency was followed suddenly by a slight excess, the latter would have to burst a way across the shallow sill as a small wave with a steep front; and this, clearing the way before it, drained the pool considerably, thus preparing for the formation of a second wave. This reasoning, I repeat, is only valid for a certain scale of things. If the dimensions be greatly changed, the relative importance of the factors would also be changed. This origin of the wave by the filling and emptying of a sort of pool accounts for the fact that the interval between successive waves on the Guntenbach was never less than several seconds, whereas on the Grünnbach the period at first was much less than a second. When the Guntenbach was flowing sluggishly, with less water than usual, the period was always a long one, for it took a long time to fill and empty the pool. When there was very little water, the formation of the waves appeared to be capricious, a long interval occurring, during which the stream flowed steadily, to be succeeded by a fairly regular series of waves. On the small conduit of St. Maurice,[1] already referred to, this capriciousness was still more marked, and more obviously depended upon some slight variations in the strength of the stream, caused one knows not how. It is evident that in this case we have something rather like the roll-waves of the Tees on a minute scale.

The average depth in the conduit of the Guntenbach was difficult to determine on account of the inequalities of the pavement, but 2 inches was a usual amount. The speed of the current was determined at 8.5 feet per second, and the true speed of the wave at approximately 2.25 feet per second. On one occasion the depth at crest at outflow was estimated at 3.5 inches, and at the trough 2 inches.

On more than one occasion a thunderstorm filled the conduit to a depth of from 5 inches to 9 inches, and then there was absolutely no roll-wave or

[1] Average period of waves, 13·5 seconds. The conduit was only 3 feet wide, and paved with blocks extending the whole width, so that there were no longitudinal joints, which in the Guntenbach tend to spoil the wave by making unequal depths in cross-section.

THE GUNTENBACH WITH TWO ROLL-WAVES.

cadence in the outflow. The depth was, therefore, apparently too great for the effect of frictional resistance to produce an intermittent flow, and the pools of the pavement were now too insignificant to act as they did with a smaller depth of water.

I have never seen a stream with a uniform depth of more than 4 inches adopt spontaneously the intermittent flow in a series of roll-waves. The conduit of the Chauderon River at Montreux, with a depth of 6 inches, did not flow thus; neither did the much larger Veveyse River, in its conduit at Vevey, flowing swiftly at the time of snow-melting, with a depth of 48 inches.

Nevertheless, I found (after my eyes had been trained by watching well-marked roll-waves for some months) that waves progressing down-stream through the water *co-exist* with stationary waves in shallow streams, and may even be detected in deep ones, although they do not (except if caused by floods) there develop or grow so as to become conspicuous or important relatively to the other phenomena of flow. Thus (commencing with the Guntenbach), on looking closely at a standing wave (in which the depth of water was only about 2 inches) I noticed that the water here flowed gushily—*i.e.*, the excrescence of the bottom, which caused a stationary wave, also caused progressive waves. Close to Schloss Ralligen (between Gunten and Merlingen) is a short and very steep conduit, 3 feet wide, with a pavement of ribbed form, each rib extending quite across the conduit. The distance from the summit of one rib to that of the next is 6 inches, and the line of the crest of the ribs is about 0.3 inches above the line of their troughs. The depth of water covering the crests of the ribs was 0.5 inch. The appearance of the whole is that of a cascade with transverse bars of white foaming water, situated at the summit of each rib, these transverse bars showing (as is usual in cascades and waterfalls of small dimensions) a longitudinal striping, so that the form of the standing waves caused by each rib is that of a comb, the back of the comb representing the principal transverse line of white water, and the teeth the smaller longitudinal lines of white water. This, with a slight flicker, was all that I saw in 1904. But in 1905, being now aware how stationary objects fix the eye so that it cannot distinctly see moving things,[1] I tried the expedient,

[1] Conversely when moving bodies are many and conspicuous the attention is distracted from stationary objects. A good example of this may be obtained by visiting the vicinity of the Mansion House in the City of London early on a Sunday morning. Those who think that they are familiar with the sur-

which I had often found useful, of half-closing the eyes, so as to render the outlines of the stationary objects indistinct. I saw immediately that roll-waves extending the whole breadth of the conduit were dashing down the channel all the time with great speed, and at intervals of not more than half a second. Thus by varying the method of looking, it became possible to appreciate clearly the dual aspect of the phenomena of the flow. The roll-waves were no insignificant part of the whole flow, the apparent predominance of the stationary waves being due more to optical advantage than physical superiority. I made a similar observation in the roughly-paved steep conduit which carries the Verraye torrent at Veytaux (Switzerland) in the lower part of the course below the lower road.

In deep streams the down-stream progressive waves are difficult to observe, but I have no doubt that they are normally present wherever waves exist at all. If the eye be allowed to follow the stream, it is often easy to see some travelling inequalities of surface in the deep water, especially when the light is low, but it is not always clear whether they are truly waves ;

rounding buildings from frequent, or even daily, visits will probably notice many architectural features which escaped their attention during the hours of busy traffic.

still less is it usually possible to know if they are travelling through the current down-stream. If, however, the streams have gently shelving shores, and especially if these be smooth, the direction of the waves which come in upon them facing diagonally, but on the whole down-stream, indicates clearly that there are in the deep water progressive down-stream waves invisible only on account of their flatness.

Should I have the opportunity to revisit the Niagara Whirlpool Rapids, I might perhaps detect the existence of down-stream waves there, although I could not do so before I had daily practice in their detection. The fact that waves which have not a length great as compared to the depth continually multiply themselves, would of itself account for the fact that such waves tend to die out rather than to increase in deep streams. Unequal depth of cross-section, as has already been mentioned, also tends to do away with them, causing them to discharge themselves upon the banks.

UPPER PART OF FALLS AT NIAGARA, SHOWING UNBROKEN WATER.

CHAPTER XII

The sounds of running water—The gushing motion of cataracts —Conical structures produced by the break-up of a waterfall—The wave-track of a ship.

On the Sounds of Running Water

WHEN we watch the standing waves of a shallow stream and think, perhaps, of the steady state to which it is supposed to have attained, the pleasant but irregular sounds which greet the ear are evidence of momentary variations in this state, and of disturbances passing down-stream. The sound of the foaming cusped wave, if continuous, would, indeed, indicate a steady condition, although the motion at that spot is " discontinuous " in the sense that the thread of the stream is there broken; but the breaking of the cusped wave is, as a rule, intermittent. From time to time also a pretty tinkle catches the ear, a single sound, presently repeated in another place. A careful study of these sounds will greatly assist the eye in discovering the details of the stream's motion. It is upon the sounds as much as the appearance that the poetical student of Nature has relied for conveying his impressions of these scenes. Tennyson's phrase to " babble on the pebbles " is a familiar example. When he speaks of the " drumming thunder " of a great waterfall, he records by ear the partial intermittence superimposed upon a steady motion, which will be dealt with in the next section of this paper.

On Gushing Motion in Cataracts and on the Conical Structures produced by the Break-up of a Waterfall

We have seen how in a swift shallow stream the frictional retardation of the layers next to the bed imparts a gushing motion to the water, which, when the channel is straight and of uniform cross-section, produces a train of long waves of the bore form with foaming fronts transverse to the current, following one another in regular succession down the stream. In cataracts and waterfalls there is also a gushing motion, but it is irregular. In hilly or mountainous districts the noisy cataract of white water replaces the clear babbling brook with standing waves which is characteristic of undulating country, or the silent stream of the plain with its curling currents and

NIAGARA FALLS, SHOWING FLEECY APPEARANCE PRODUCED BY THE BREAKING OF THE FALLING WATER.

smooth surface. The broken water of the cataract passes too swiftly for the eye to follow its motion, and the streaky appearance is evidently due to this circumstance. On thrusting my hand into the flying water of a small cascade which comes foaming down through the Forest of Chillon I found that the real intermittence of the optically continuous motion was at once apparent, for instead of being subjected to a pressure, as from a current, the hand experienced a succession of sharp buffets.

In a cataract descending the right bank of the Gorge of the Chauderon, at Montreux, I saw well the transition from the rush of the cataract to the leap of the waterfall. Along reaches of lesser steepness the water kept to its bed, yet all whitely foaming, being torn to drops by friction with its bed; but steeper reaches were leaped by the shower of water, the leap being what one calls a waterfall. By a cataract I mean that extreme case of a torrent in which the water is all foaming.

A low waterfall of 1 foot or 2 feet in height, unless delivering water already in violent motion, generally presents to the eye a number of brilliant vertical stripes, having a lustre as of polished metal, continuous from top to bottom, and practically steady in position.

The appearance of the water in a high waterfall is quite different, for the water is more opaque or milky, there are none of these brilliant stripes, and (especially if the eye be allowed to follow the water in its fall) it is seen to be patchy, the patches being more or less conical or V-shaped. Photographs of waterfalls sometimes show them, when the shutter of the camera works with sufficient rapidity. Livingstone thus describes these characteristic bodies as he saw them at the Victoria Falls of the Zambesi:[1] "On the left side of the island we have a good view of the mass of water . . . as it leaps quite clear of the rock, and forms a thick, unbroken fleece all the way to the bottom. Its whiteness gave the idea of snow, a sight I had not seen for many a day. As it broke into (if I may use the term) pieces of water, all rushing on in the same direction, each gave off several rays of foam, exactly as bits of steel, when burned in oxygen gas, give off rays of sparks. The snow-like sheet seemed like myriads of small comets rushing in one direction, each of which left behind its nucleus rays of foam. I never saw the appearance referred to noticed elsewhere. It seemed to be the effect of the mass of water leaping at once

[1] "Missionary Travels in South Africa."

THE BREAKING WATER OF NIAGARA FALLS, TAKEN FROM S.S. *MAID-OF-THE-MIST.*

clear of the rock, and but slowly breaking up into spray."

The phenomenon is very noticeable in the comparatively thin sheet of water which forms the American Falls at Niagara, but the 20-feet-thick green water at the "Horse-shoe" retains its homogeneity much better. This fact indicates that the partial break-up of a waterfall is not due so much to friction with the air as to other causes, chief among which is, presumably, the dynamically unstable condition of a sheet of water falling under the constant acceleration of gravity. This partial breaking up, which, as Livingstone well indicates, is an early stage of the process by which the water will, if it falls far enough, be finally resolved into spray, must be greatly hastened in the case of a waterfall fed by a stream already markedly intermittent in its motion. I have already described (p. 273) the unsteady motion of the shallow water in the rapids above the American Falls. The late Professor J. Tyndall says[1] of the Falls: "The descent finally resolves itself into a rhythm, the water reaches the bottom of the fall in periodic gushes." And Captain Basil Hall, in the Cave

[1] "Niagara," a discourse delivered at the Royal Institution of Great Britain, April 4, 1873, published in the *Fragments of Science* (p. 178).

of the Winds, behind the falling sheet of water, found that the barometer pulsated. The cones in the American Falls appeared to follow one another in swift succession, but in watching the fall of the water of the Tschingelbach, at Burglauenen, near Grindelwald, Switzerland, May 22, 1904, where the cones were very perfect, but the volume of water small, I concluded that the apparent swiftness at Niagara was due to the great number of cones passing confusedly. So also do snow-flakes seem to pass the eye rapidly when we look through a long column of air, standing out of doors, but if we watch from the interior of a room, so that no flakes pass close to the eye, it is seen that for the most part they are subsiding slowly through the air.

The conclusion was confirmed when I next viewed the Tschingelbach Fall. The amount of water was then much diminished, and the fall was coming down in several separate threads of water instead of in a broad sheet. The cones in each of these threads of falling water followed one another in an orderly and unhurried manner,[1] the

[1] In a narrow waterfall at Isetwald, on the Lake of Brienz, I saw the cones, which were close together near the commencement, become widely separated as their velocity increased under the action of gravity.

FALLS OF THE TSCHINGELBACH, BURGLAUENEN.

speed of each individual cone increasing as it fell, the pointed shape sometimes becoming more pronounced, until at last the forces making for disintegration dissipated the structure in spray.

This appearance is closely paralleled in the case of the snow avalanches seen from Grindelwald when they leap the edge of precipices on the Eiger or the Mettenberg. There is the same appearance of cones amidst the white clouds of snow, the cones increasing in speed, with sharpening points, and finally bursting in dust. The drawing out to finer lines as the cone descends is easily understood if we remember the acceleration of gravity, and the air-resistance at the edges, and the greater retardation of the finer particles. In water it is the same. When jets are thrown upwards, as from the "Horse-Shoe" at Niagara, the sharpening of a cone proceeds still more quickly.

On visiting the Tschingelbach in June, 1905, I saw the water-cones in very fine development, and they were even united into roughly transverse bands. Between these the veil of misty spray was thin and semi-transparent. I then perceived that there was a local cause for their unusually fine development in the last big leap of the fall, for the water above slides over a steep face of rock, where it goes into fairly well defined roll-waves.

The ranging of the water-cones in roughly transverse bands is due to this cause; they gradually lose their transversality as they descend.

Below a waterfall near Matten, Grindelwald, the waters flow steeply over a bed of rock, which gives a uniform, small depth to the stream, which flows in roll-waves owing largely to the initially discontinuous character of the motion of the falling water.

Below one of the principal leaps of the Giessbach Falls (Lake of Brienz) I also saw down-stream waves, which, however, soon lost their transversality on entering the swift channel of exit from the pool.

When any waterfall or cascade discharges into still, deep water, progressive trochoidal waves proceed outwards in all directions, as may be prettily seen, for instance, in the ornamental waters of the public gardens at Buxton.

On the Wave-track of a Ship as seen on the Swiss Lakes

The late Lord Kelvin described [1] the dual system of waves which originates at the bow of a ship. They are the diverging series, the fronts of which

[1] "Popular Lectures and Addresses."

WATER ROCKETS PROJECTED UPWARDS FROM THE FOOT OF THE HORSESHOE FALLS, NIAGARA.

make an angle with the ship's course, and the transverse series which lie across her course, travelling in the same direction. Leaving out of account the first two or three diverging bow-waves, every wave of this series has a front concave to the direction of advance. The transverse series have fronts convex to the direction of their advance. They are flatter than the diverging waves, and therefore less conspicuous if the water be ruffled. This whole system of waves is bounded on the right and left by two imaginary straight lines, each making an angle of $19\frac{1}{2}°$ with the ship's course. A similar dual series of waves originates from the stern. The pattern of waves originating from the bow or from the stern, as deduced mathematically, satisfies all that is usually visible at sea.

Being anxious to see ship-waves undisturbed by the waves of swell or wind, I decided to make observations on the placid waters of Swiss lakes. I began on the Thunersee during the fine summer weather of 1904, and continued the observations at Montreux, on the Lake of Geneva, in the spring of 1905. On still mornings the surface of the Thunersee was frequently as smooth as plate-glass, without any ruffle or darkening by even the gentlest breeze.

Under these conditions I found that the thwart waves are more conspicuous relatively to the diverging waves than in rougher water, and that their relative prominence is further increased when the wave-track is viewed from a height. At altitudes of from 300 to 800 feet on the steep slope above Gunten, opposite to Spiez, the number of visible thwart-ship waves in a single series must have amounted to hundreds, the water looking like corded silk. Unfortunately, the condition of glassy water is often accompanied by a slight haze, which makes it impossible then to obtain a strong photograph.

I saw nothing in the appearance of the train of thwart waves different from that indicated by Lord Kelvin's diagram, and nothing different from what is seen at sea, except their greater distinctness. The case of the diverging waves, however, was very different. Only the outer edge of the group presents the uninterrupted concave fronts of the diagram. Behind this comes a row of notches in the wave-fronts, which row appears from a distance as a strongly marked band, light or dark according to the circumstances of reflection. Standing near the stern of a steamer, I was able to see distinctly that the first notch occurred where a diverging wave of the bow series was crossed by the first diverging wave of the series which

WAVE-TRACK OF STEAMER ON THUNERSEE, SHOWING THWART-SHIP AND DIVERGING WAVES.

originates at the stern. The steamer which showed this best was the *Spiez,* a small screw vessel, the others being paddle steamers. Behind this row of notches (*i.e.*, nearer to the line of the ship's course) were many other rows. I have counted in a good light as many as eighteen of these "interference bands" as I term them. When the water is quite glassy they are sometimes more conspicuous than the individual waves. The photograph reproduced in the Plate on page 361 was taken on Coniston Water. It shows, not only the notches in the wave fronts, but, on the right, the vertical inflection on the crests of the diverging waves caused by interference. This causes the crest of the diverging waves to appear as a pair of dark stripes separated by a broader bright stripe. The circumstance under which the photograph was obtained was peculiar. There was a fine drizzling rain when I started for a tour down the lake by the steam gondola, so I left my camera behind out of concern for its welfare. I found that the whole surface of the lake was covered with a thin scum, which appeared to consist of a very slight film of oily soot, possibly from the smoke of the furnaces and factories which are some miles distant at Ulverston and Barrow. The surface being in this condition, the vessel left a wonderful train of waves behind. This suggests that by dripping oil out behind a vessel one might succeed in showing the detailed pattern of the ship-waves even when there is a slight breeze on a lake. I had to do the double journey before I could get my camera, and the photographs were taken on the second journey down the lake.

The effect of interference between the diverging waves from bow and stern was noticeable in the series of breakers which came in upon the beaches near Gunten after the passage of a steamer on the Thunersee. The surf was found to be interrupted by lulls during which the breakers were much smaller.

When observing from the ship, or from a position near her, the strong curvature of the fronts of the individual diverging waves is a marked feature of the wave-track. When, however, I went to a considerable height upon the hillsides in order to obtain a bird's-eye view of the wave-track I often passed the distance where the waves were individually distinct or even discernible. Curved lines then ceased to be seen and were entirely replaced by lines which were of rigid straightness whenever the ship was running a straight course. When we are near, the case is similar to that described in the phrase " one cannot see the wood

WAVE-TRACK OF STEAMER ON CONISTON WATER, SHOWING INTERFERENCE BANDS BETWEEN DIVERGING WAVES OF THE BOW AND STERN SERIES.

for the trees"—*i.e.*, one cannot see the group for the waves. At a distance, when the trees are no longer individually discernible, one makes out the size and shape of the wood. Similarly, when one can no longer distinguish individual curved waves one sees at once in startling distinctness Lord Kelvin's straight-lined boundary, marking the limit to which the waves appreciably extend. In addition to this group-line there is another, also originating at the ship, which marks the rear of the diverging series of waves. Thus the wave-track of the ship is generally reduced at a distance to four straight lines, radiating from the ship, two on either side.

When this is the appearance presented to the naked eye a pair of field-glasses reveals the individual diverging waves. Sometimes also, especially when the ship is directly receding, the space between the inner boundaries of the diverging waves is seen to be filled up by a cross-barring of the flatter and broader thwart waves.

The visibility of the waves depends upon circumstances of reflection, and these vary much with the direction of the ship's course relatively to the observer and to the bright and dark parts of the sky and land. Thus, it sometimes occurs that the straight line forming the outer boundary of the visible diverging disturbance is not the outer edge of the bow-waves, but the first interference band of these and the stern-waves. On the approach of the vessel to Gunten on her way from Spiez I have noticed individual curved bow-waves come into view beyond the straight line which had formed the visible boundary at a greater distance. On examining the line of the inner boundary of diverging disturbance with the field-glasses I have seen it as a band, skew-barred by the individual diverging waves. These, I presume, are the rear members of the stern-waves, which ought to extend within the limits of the bow-waves. They here make a somewhat small angle with the ship's course and are consequently much crowded, with a very small wave-length.

I have never detected any rearward boundary-line to the system of transverse waves, nor have I seen light or dark bands indicative of interference between those originating from the fore-part and after-part of the ship respectively.

Ship-waves, which maintain their form unchanged and keep the same positions relatively to the moving agent which produces them, are classed as stationary or standing waves. A curious progressive condition is, however, seen among them when two steamers pass one another

WAVE-TRACK OF STEAMER ON CONISTON WATER, SHOWING INTERFERENCE BANDS AND DOUBLE-CRESTED DIVERGING WAVES.

WAVE-TRACK OF STEAMER ON LAKE LEMAN.

WAVE-TRACK OF STEAMER ON LAKE LEMAN, SHOWING, ON THE LEFT, THE INNER BOUNDARY OF GROUP OF DIVERGING WAVES.

on opposite courses at such a distance that the outer boundaries of their wave-tracks meet at a small angle. On the glassy waters of the Thunersee, and on a bright day, the new disturbances of reflection run along the line of meeting in short bars of light which flash across the water at almost lightning speed, by which I mean a speed much greater than that of any railway train or of any bird in flight.

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